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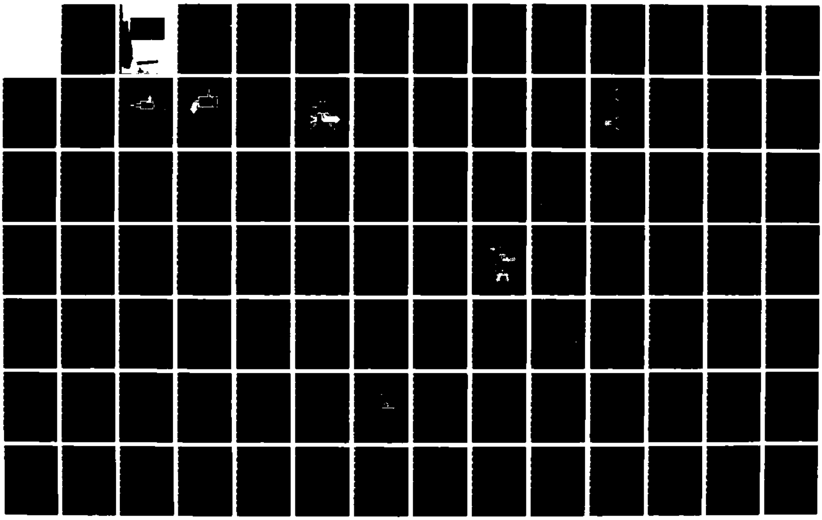

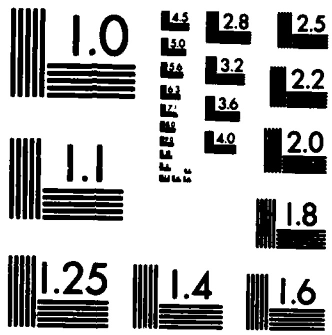
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DEPARTMENT OF OCEAN ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

DESIGN OF A SIMPLIFIED AIR REGULATOR FOR DIVERS

BY

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(1979)

SUBMITTED TO
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DESIGN OF A SIMPLIFIED AIR REGULATOR FOR DIVERS

by

Benjamin Kenneth Miller, Jr.

Submitted to
the Departments of Ocean and Mechanical Engineering
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of the requirements for the Degrees of
Master of Science in Mechanical Engineering and
Master of Science in Naval Architecture and Marine Engineering.

ABSTRACT

A high volume, low pressure loss, balanced poppet valve was designed for use on demand type open-circuit underwater diving units. This supply valve, the EX-1, acts as a diver's second stage regulator providing air, on demand, to the diver with minimal breathing effort. The prototype EX-1 was fabricated and tested in January 1984 by the Navy Experimental Diving Unit, Panama City, Florida. Test results showed that the EX-1 met the U.S. Navy performance requirements for helmet mounted second stage demand regulators. However, the valve/seat arrangement leaked excessively.

Final modifications to the poppet valve and seat were made, eliminating aerodynamic forces which had acted on the poppet valve's seating surface. Additionally, a compliant seat was used which eliminated gas leakage. Brief testing of the improved EX-1 prototype on May 4, 1984 indicated that performance was equivalent or superior to performance of the best commercial second-stage demand regulators currently available.

Thesis Supervisor: Dr. Carl R. Peterson
Title: Associate Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

I wish to thank Professor Carl R. Peterson for his help and guidance as my Thesis Advisor. Without his ideas and enthusiasm the EX-1 would not exist. Also, I am grateful to my friend Jim Middleton, Senior Project Engineer, Navy Experimental Diving Unit, whose enthusiastic support and diving experience were instrumental in the fabrication and successful testing of the EX-1. The help of his colleagues Paul Morson, LT(CF) and E.S. Morrison, FCPO(RN), was invaluable. Fabrication of the prototype was possible because of the joint efforts of Valton E. Sinard, Machinest, Ron L. Juggenheimer, Shop Foreman, and Howard Turner, Planner and Estimator. Finally, I would like to acknowledge the help of the following engineers of the Naval Coastal Systems Center, Carter Somerset, Mike Trouffer, Barry Miller and Jim Preston. It was the combined help of all the above and many others, too numerous to mention, that made this report possible.

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Glossary

Abbreviation	Definition
BPM	breaths per minute
cm H_2O	centimeters of water pressure (differential)
EX-1	experimental unit one, the prototype open-circuit demand regulator
fsw	feet sea water
HeO_2	helium-oxygen breathing gas
h.p.	high pressure
I.D.	inside diameter
kg·m/l	breathing work in kilogram meters per liter ventilation
LBF	pounds force
LPM	liters per minute (flow rate)
MOD 0	The EX-1 design tested during January and February 1984, incorporating an O-ring seal on the poppet valve
MOD 1	The EX-1 design tested in May 1984, incorporating a knife-edged poppet valve
NEDU	Navy Experimental Diving Unit
ΔP	pressure differential
psig	pounds per square inch gauge
RMV	respiratory minute volume in liters per minute

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1. NEDU Report 2-80, "Evaluation of Commercially Available Open Circuit Scuba Regulators," James R. Middleton, March 1980.

2. Baumeister, Avallone, Baumeister, <u>Mark's Standard Handbook for Mechanical Engineers</u>, McGraw-Hill Book Company, New York, N.Y., 1978.

1. Introduction

1.1 History

Long before Jacques-Yves Costeau invented the Aqua-Lung, divers have worked under the waters of the world. The diving suit with which most individuals are familiar is the U.S. Navy's ancient Mk-5 which incorporates a large copper helmet, a canvas suit, heavy lead boots, and an umbilical to supply the diver with air. Modern technology has provided major improvements for working divers, increasing the divers' ability to perform assigned tasks.

The ease with which a diver can obtain his breathing gas directly affects his work output. If a diver must expend a large amount of work to breathe, the potential for additional constructive work is low. For this reason the diver's underwater breathing apparatus is a critical piece of equipment.

Breathing apparati can vary, depending on the application. Basically, two types exist: (1) open-circuit, and (2) closed-circuit. In the open-circuit unit, breathing gas is supplied to the diver, then exhaled and lost to the surrounding water. For a closed-circuit system the gas exhaled by the diver is recovered and recycled. The equipment needed to support a closed-circuit unit is often cost- and/or size-prohibitive. As a result, most working divers and the majority of sport divers utilize open-circuit units.

Most open-circuit breathing apparati are amazingly similar in design. Usually, a high-pressure, large-volume gas source supplies the diver via a series of pressure regulators and umbilical hoses. Efficient performance of these units, regardless of diver depth and gas demand, is vital. The design and manufacture of a high-efficiency, open-circuit, under-water breathing apparati is the goal of the commercial diving industry.

1.2 Problem Statement

A demand-type open-circuit underwater breathing apparatus supplies gas to the diver during the inhalation portion of the breathing cycle. Exhaled gas vents to the surrounding water through exhaust ports. The performance of a diving system's first stage directly determines the inhalation effort required by divers using current, state-of-the-art equipment. The first stage must supply air at a sufficiently high pressure and volume to the second stage in order for the second stage to function properly. As inhalation effort increases with depth and respiratory rate, second-stage supply pressure from the first stage typically decreases.

As diver depth increases the density of the breathing gas increases in proportion to the local pressure. While the diver's respiratory rate (i.e., volume flow rate) may remain unchanged as depth increases, greater physiological effort is required to breathe the denser gas, independent of

the equipment being used. Additionally, larger flow losses occur within the underwater breathing apparatus as gas density and/or respiratory rate increase. Due to these factors, a diver's inhalation effort tends to increase whenever the depth and/or the respiratory rate increase.

The spring/valve mechanism of most second stage regulators is designed to function with minimum inhalation effort when supplied with a constant 125 to 200 psig above ambient pressure from the first stage (first-stage supply pressure may be 65 to 200 psig). This intermediate pressure from the first stage is normally set under static or no-flow conditions by the manufacturer. Upon inhalation this pressure drops as the air flows from the first to the second stage. As a diver descends and increases his work rate, the increased flow from the first to the second stage causes the pressure drop below the static setting to increase dramatically. Consequently, the second stage may no longer be receiving air at a pressure and volume sufficiently high to effectively meet the diver's inhalation needs, resulting in increased inhalation effort. For example, a regulator with a static intermediate pressure of 140 psig above ambient can usually operate efficiently with dynamic pressures as low as 115 psig above ambient. Pressures lower than this during inhalation generally result in significantly increased inhalation effort (and breathing work) in current second stage regulators.

1.3 Solution

Development of a helmet-mounted second stage regulator which was unaffected by large intermediate pressure fluctuations would greatly improve breathing performance. A high-volume, low-pressure loss, balanced piston supply valve capable of continuous 'open-shut' operation would provide this improvement.

2. Development Approach

2.1 Basic Concept

The goal of this project was to develop an air valve capable of: (1) high volume gas flows, with minimal diver inhalation effort, and (2) operation which involves continuous opening and closing cycles of a poppet valve. Additionally, since the valve's operation is critical to the life of a diver, at whatever depth, reliability is vital.

A simple design capable of satisfactory operation in a harsh environment was preferred. It was felt that simplicity of design would improve reliability, manufacturability and maintainability. Most second stage air valves (regulators) utilized today are simple designs but almost all suffer from one major drawback -- diver inhalation effort increases unacceptably during high work-rates below 100 feet sea water (fsw).

With few exceptions, current second stage regulators share the same basic design (Figure 1). High pressure gas supplied by the first stage acts axially on the face of a small poppet valve, tending to open the valve. This pressure force is an appreciable fraction of the total force necessary to open the valve against the return spring. The remainder of the force necessary to open the valve is supplied via diver inhalation effort. Inhalation creates a decrease in pressure below ambient which, acting on a three-inch diaphragm and through a series of levers, generates the force necessary to open the valve (Figure 1). A decrease in supply pressure to the second stage during inhalation requires additional opening forces be supplied by the diver. The result is an increase in the diver's inhalation effort, or increased breathing work.

A simple second stage regulator which is unaffected by large fluctuations in supply pressure was needed. Balancing the valve such that supply pressure exerts no axial force on the valve would eliminate, or at least minimize the effect of supply pressure on second stage performance (Figure 2). Spool valves offer a geometry that exhibit this desired behavior.

Next, the precise method of operation of a spool-type valve was to be determined. Sliding seals and ultra-close tolerances of such valves were ruled out due to high frictional losses and potential clearance and dirt problems.

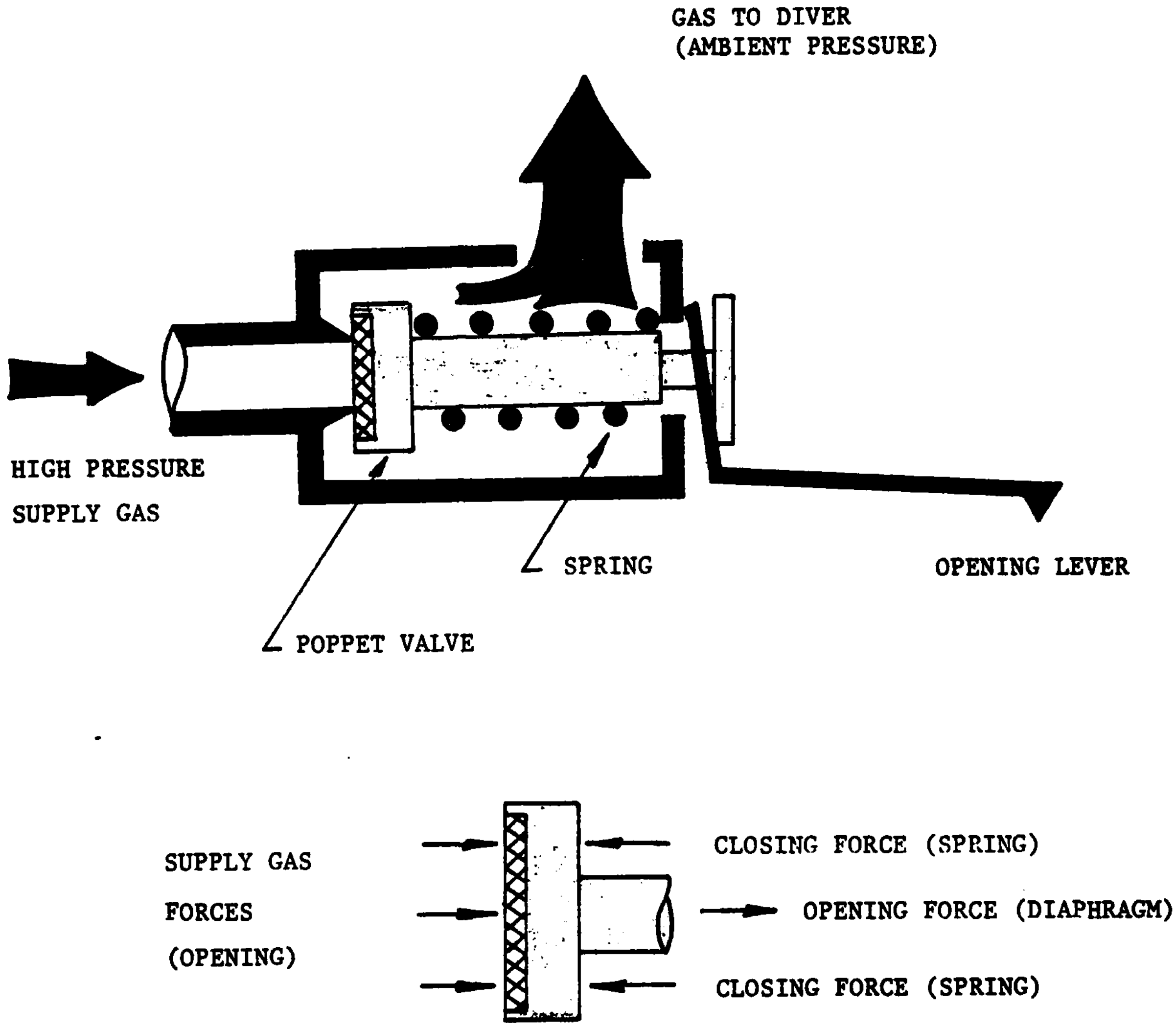


FIGURE 1. CONVENTIONAL POPPET VALVE
AND FORCE BALANCE

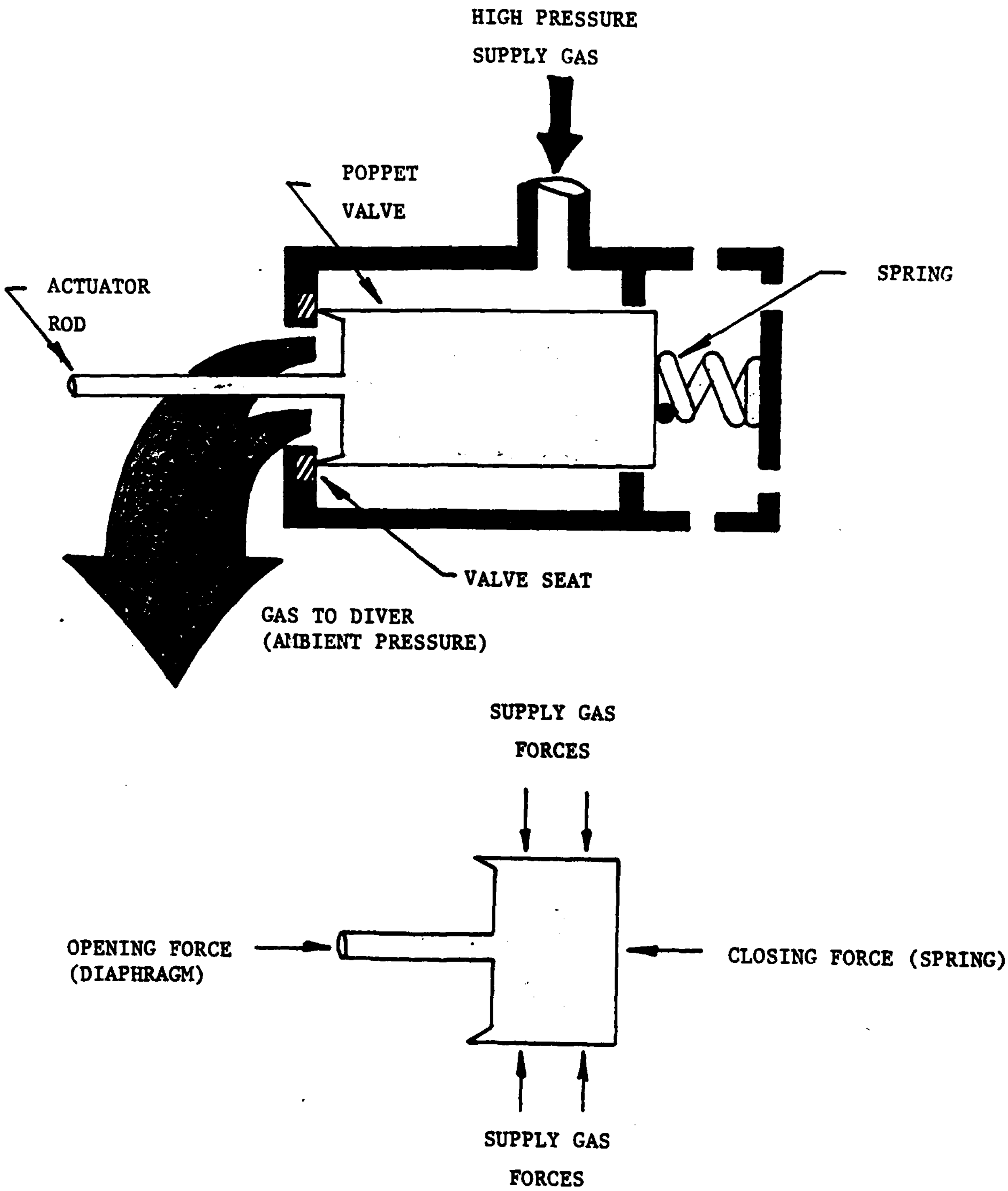


FIGURE 2. EX-1 POPPET VALVE (MOD 1)
AND FORCE BALANCE

An air-bearing valve support concept was considered to minimize friction but gas loss and the possibility of sea-water contamination/fouling threatened performance reliability. Ultimately, the compromise design of Figure 3, a very low-force balanced poppet valve, was decided upon. This design provides simplicity and reliability, and reduced dependence on pressures supplied by the first stage.

2.2 Schedule

The Navy experimental diving unit offered to build and test a prototype regulator, dubbed the EX-1, if the design could be complete by January, 1984. To meet this deadline a relatively rigid schedule was developed. First, a preliminary design was established in mid-November, 1983. Based on this design, a simple mathematical model assuming quasi-steady state flow was developed and computerized results were obtained the last week of December, 1983. Final design changes were also made during this week.

The author spent the month of January 1984 at the Navy Experimental Diving Unit, Panama City, Florida, assisting in the fabrication of the prototype EX-1 MOD 0. Once fabrication was complete, initial testing was performed to correct obvious flaws. Final testing occurred on 30-31 January, 1984. Data reduction and analyses took place during the month of February, 1984. Valve and seat modifications were made and the EX-1 MOD 1 was tested on 2 May 1984. Data reduction and analysis were conducted following the test.

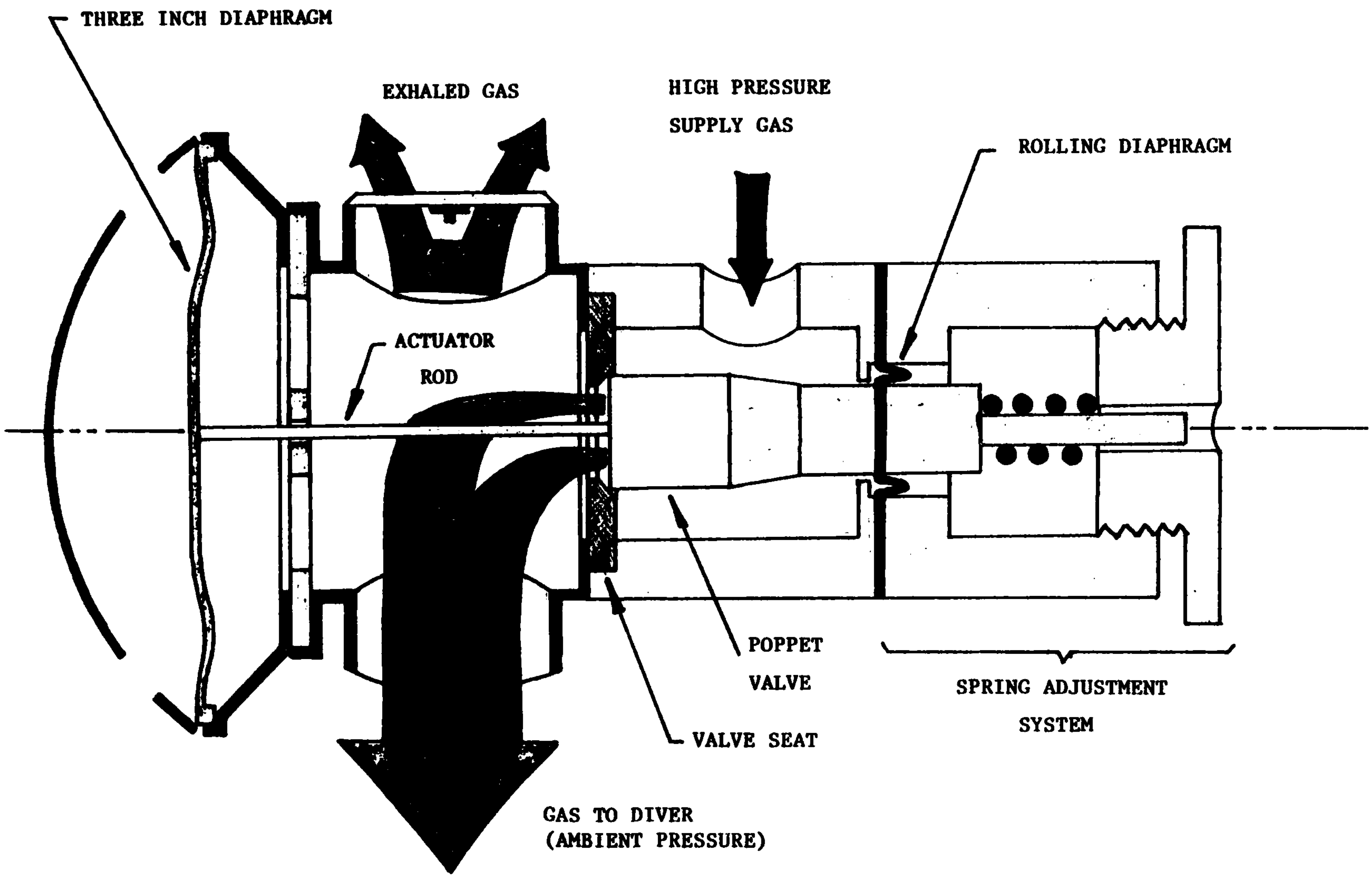


FIGURE 3. EX-1 SECTION VIEW (ORIGINAL DESIGN)

3. Regulator Design

3.1 Components

The EX-1 regulator consists of five major components/systems:

(1) Regulator Body

(2) Poppet Valve and Seat

(3) Rolling Diaphragm

(4) Spring Adjustment System

(5) Breathing Bowl

Figure 3 provides a cross-sectional view of the EX-1.

The regulator body houses the poppet valve, seat, and the rolling diaphragm. Supply gas is provided via a fitting attached to the regulator body. The breathing bowl and spring adjustment system are attached to the regulator body at opposite ends.

The poppet valve is balanced with respect to supply gas pressure, in the sense that supply pressure generates no net axial force on the poppet. For the EX-1 MOD 0 the valve seat is cut at a 45 degree angle. The O-ring installed in the edge of the spool valve contacts the valve seat when the valve is shut, stopping gas flow to the diver. The EX-1 MOD 1 poppet valve and seat utilized a knife edge on the valve and a compliant rubber valve seat.

A rolling diaphragm was utilized to provide a frictionless seal for the EX-1. The diaphragm isolated the internal gas chamber from external sea water and was capable of operation with differential pressures in excess of 200 psig. To balance supply gas axial forces the diameter of the poppet where it seals against its seat had to be the same as the rolling diaphragm's effective piston diameter. Theoretical effective piston diameter for the selected rolling diaphragm was 0.310 inches.

The spring adjustment system allows valve closure force to be adjusted to optimize breathing conditions. Too high a force requires excessive breathing effect, while too low a force permits leakage upon closure. This system was designed to allow a variety of compression springs to be sampled, until one spring was finally selected for the unmanned test. The diver's mouthpiece, an exhalation check valve and a three-inch diaphragm are the major components housed in the breathing bowl. Standard components were used for these items. Gas to and from the diver's mouth passes through the mouthpiece.

3.2 Regulator Operation

The diver's mouthpiece is part of the breathing bowl, as is the exhalation check valve. As the diver inhales, a small differential pressure is developed between the interior of the breathing bowl and the ambient sea conditions surrounding the regulator. This differential

pressure deflects the diaphragm inward. Movement is translated via the rigid actuator rod, lifting the poppet valve off its seat. High-pressure gas passes through the open valve, expanding into the breathing bowl. This gas supplies the diver and, at the same time, tends to decrease the pressure differential. As inhalation ends, the differential pressure goes to zero.

The spring adjustment system, attached to the regulator body, continuously exerts a small closure force on the poppet valve. During diver inhalation, the opening force exerted by the three-inch diaphragm by way of the actuator rod is large enough to overcome the spring force, opening the valve. As the differential pressure between the breathing bowl and ambient is reduced the three-inch diaphragm's opening force decreases and the closure force of the spring closes the valve, stopping gas flow. During the diver's exhalation phase, exhaled gas leaves the regulator through the breathing bowl's exhalation check valve.

To achieve low diver inhalation effort it is necessary to keep spring closure force and frictional forces small with respect to the three-inch diaphragm's opening force. This presents a problem because zero gas flow is difficult to achieve using small closure forces. In an attempt to obtain zero gas flow when the valve closed, several poppet valve and seat designs were fabricated and tested.

Final design changes involving the EX-1's poppet valve were incorporated in April 1984, allowing for one day of testing at the Navy Experimental Diving Unit. Figure 2 shows the knife-edged poppet valve and the compliant rubber seat used during EX-1 MOD 1 testing. This modification of the poppet valve and its seat eliminated the surface area associated with the O-ring seal of the EX-1 MOD 0 (Figure 4), improving the EX-1's performance and stopping gas leakage past the poppet valve and its seat.

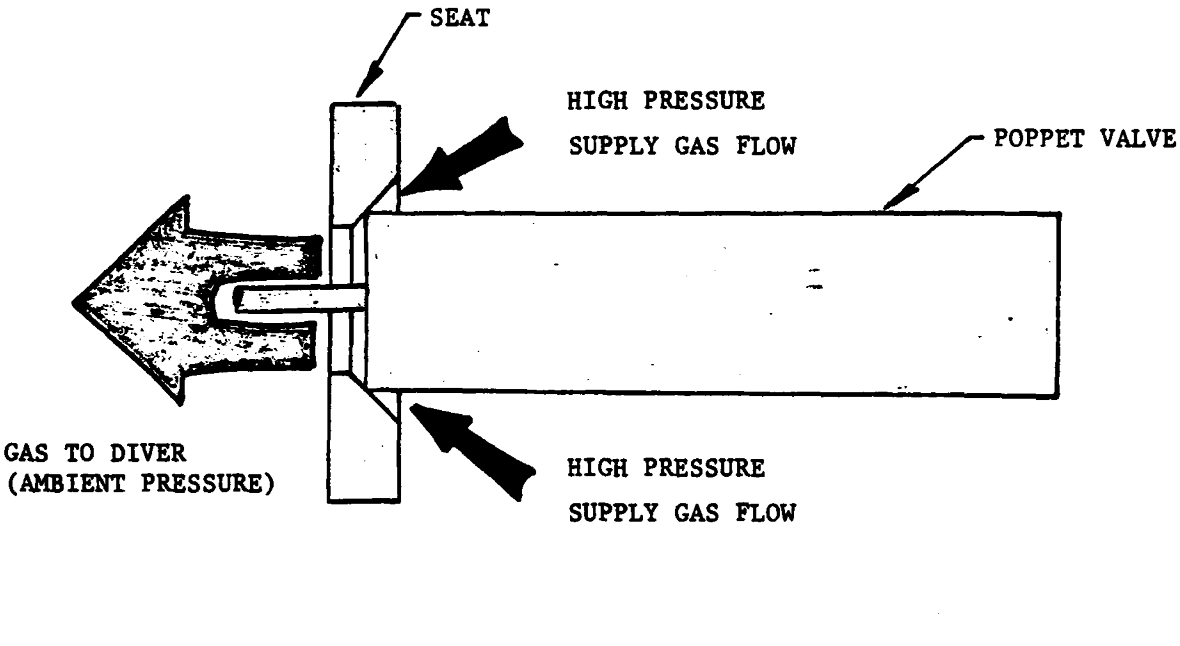
4. Tests

Testing of the EX-1 MOD 0 occurred during January 1984 and testing of the MOD 1 prototype followed in May 1984. Testing took two forms: (1) manned tests (dry); and (2) unmanned tests (wet).

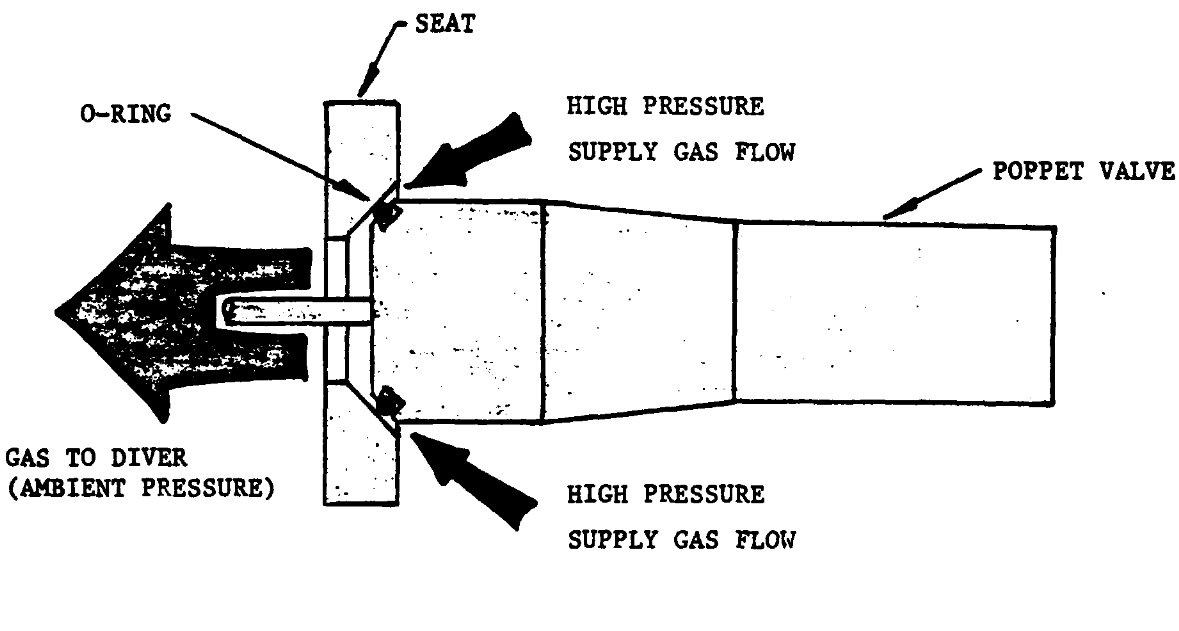
4.1 Manned Tests (Dry)

This was an informal, "go-no go" test of the EX-1 prototype. All initial problems needed to be identified and corrected prior to the unmanned tests.

Manned tests were performed by connecting the EX-1 regulator to a regulated gas supply. The unit was then breathed manually by the author, out of water, to determine a setting for the spring adjustment system which provided lowest breathing effort and minimal gas leakage. Additionally, manned testing identified the poppet valve and seat combination which offered the lowest gas leakage. Once



(A) ORIGINAL EX-1 POPPET VALVE AND SEAT



(B) MODIFIED EX-1 POPPET VALVE AND SEAT
INCORPORATING AN O-RING (MOD 0)

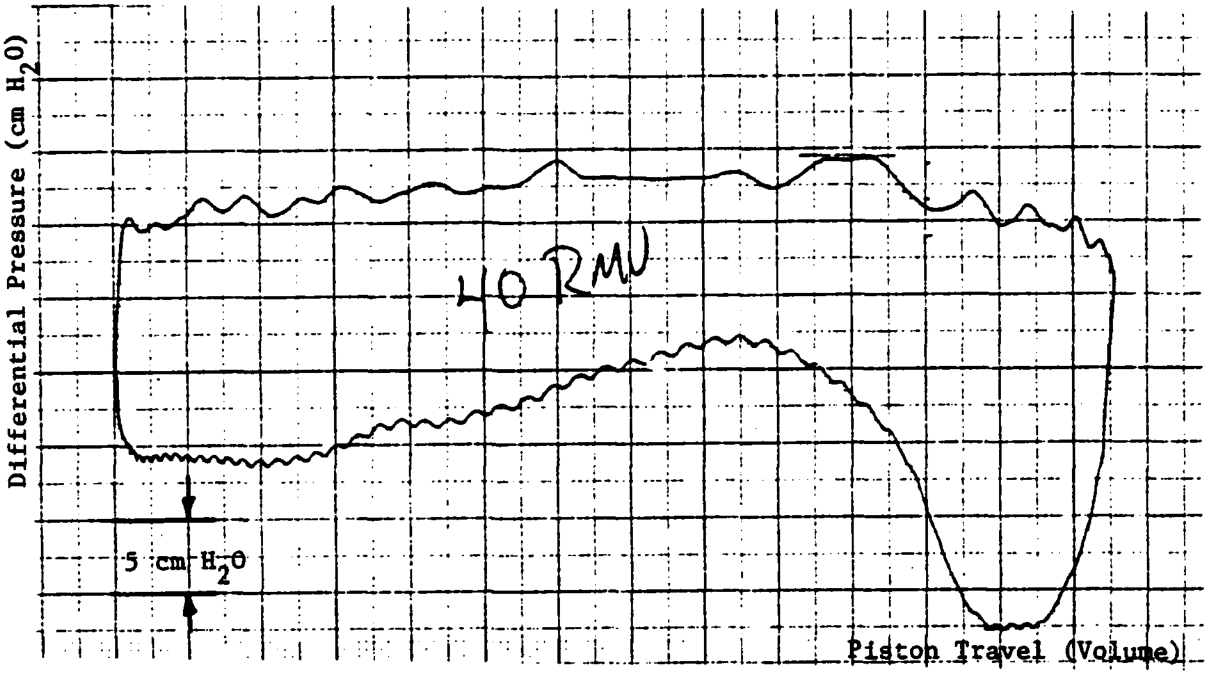
FIGURE 4. ORIGINAL AND O-RING MODIFIED
EX-1 POPPET VALVE

acceptable operation was achieved during manned tests, the unit was subjected to rigorous, calibrated and fully documented unmanned testing.

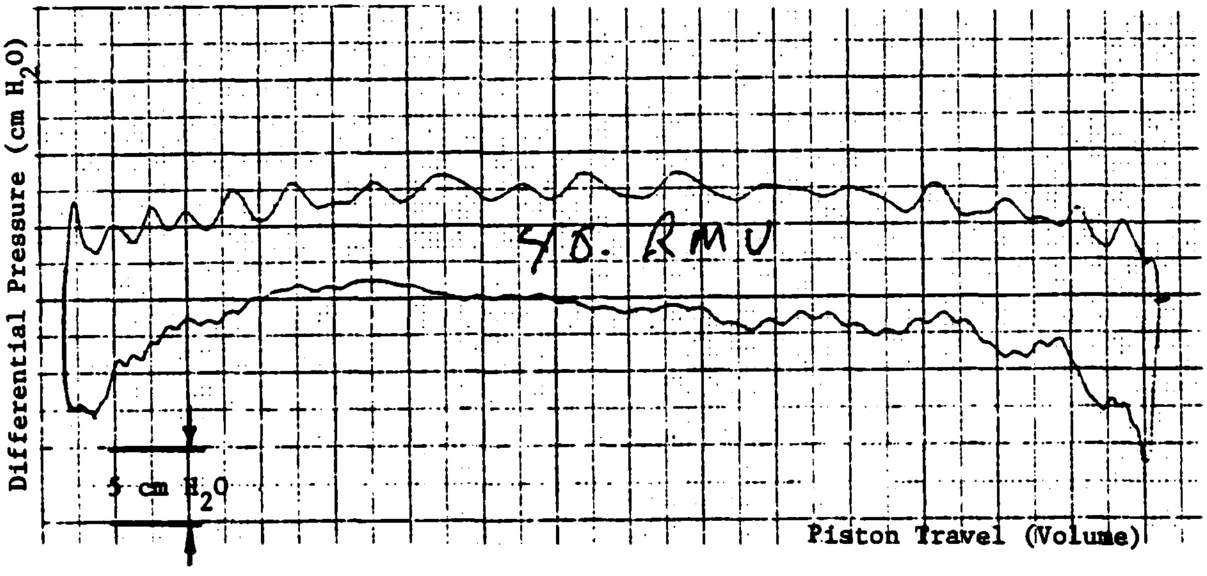
4.2 Unmanned Tests (Wet)

The EX-1 regulator was tested in accordance with Navy Experimental Diving Unit Report No. 3-81 (Appendix B). All testing occurred at the Diving Unit's Experimental Diving Facility and utilized Navy equipment and personnel, as per the test plan in Appendix C.

Levels of breathing work per liter of gas versus depth were obtained during tests. By measuring the breathing-bowl differential pressure during inhalation and exhalation and plotting this with respect to the gas volume of one inhalation, a pressure volume loop is created. As described in Appendix B, the area inscribed by this loop represents the physiological breathing work which corresponds to the test conditions and the regulator being tested. Figure 5 shows two pressure volume loops for: (1) the EX-1 MOD 0 at 50 psig supply, 198 fsw, 40.0 RMV, and (2) the EX-1 MOD 1 at 50 psig supply, 198 fsw, 40.0 RMV. In this manner it was possible to determine the effort a diver must exert to breathe when using a demand regulator. All data was tabulated and plotted, then compared with the test results of other demand regulators (Reference 1).



(A) EX-1 MOD 0: 50 psig supply, 198 fsw, 40.0 RMV,
Work-of-Breathing = 0.167 kg·m/ℓ



(B) Ex-1 MOD 1: 50 psig supply, 198 fsw, 40.0 RMV,
Work-of-Breathing = 0.083 kg·m/ℓ

<u>Figure 5</u>

<u>Pressure Volume Loops</u>

4.2.1 Performance Goals

Navy performance goals vary, depending on the type of underwater breathing apparatus being developed. The EX-1 regulator was designed for use with the helmets or full face-masks utilized in saturation diving (i.e., helium/oxygen breathing gas mixtures). By Navy standards, maximum work-of-breathing should not exceed 0.18 kilogram force-meter per liter (kg-m/l) at a breathing rate, or respiratory minute volume (RMV) of 62.5 liters per minute (LPM), at depths to and including 132 feet sea water (fsw), using air as the breathing gas. This goal was established by the Navy as it represents the best performance of existing state-of-the-art, open-circuit demand regulators.

While peak exhalation and inhalation pressure goals are not rigorously established by the Navy for this type of regulator, peak values in excess of 20 cm H_2O are considered unacceptably high, indicating that extreme effort would be required by the diver to initiate gas flow. Such measurements were recorded during unmanned tests.

4.2.2 Test Set-Up

Detailed testing of a demand regulator requires a great deal of sophisticated equipment. Since the Navy Experimental Diving Unit's Experimental Diving Facility is designed to perform such tests on a routine basis, set-up time was minimal. The EX-1 and test equipment were set-up in accordance with NEDU Test Plan 84-07 (Appendix C).

A simulated umbilically supplied diving system was fabricated to support the evaluation. The system consisted of a five-foot length of 0.5 inch inside diameter (I.D.) "swan" hose, connected to a hyperbaric chamber's air supply penetrator. The "swan" hose was then connected into a 3/8 inch I.D. U.S. Divers Corp Royal Aqualung intermediate pressure hose. This, in turn, supplied the EX-1 regulator. A first stage regulator was not incorporated to supply the EX-1. The EX-1's adjustable spring system was adjusted to obtain an acceptably small closing force with minimal leakage when seated.

A highly sophisticated, piston-type breathing machine was used to simulate the following breathing rates:

(1) 22.5 RMV (Light Work Rate)

(2) 40.0 RMV

(3) 62.5 RMV (Moderately Heavy Work Rate)

(4) 75.0 RMV

(5) 90.0 RMV (Extreme Work Rate)

A sinusoidal breathing waveform was used. Each work rate was maintained at the following depths while the data prescribed in Appendix C were recorded:

(1) 0 fsw

(2) 33 fsw

(3) 66 fsw

(4) 99 fsw

(5) 132 fsw

(6) 165 fsw

(7) 198 fsw

(8) 300 fsw

A complete set of data was recorded for the above conditions using a supply pressure of 50 psig above ambient (a static setting, simulating a limited supply capacity). Following the completion of this test, supply pressure was raised to 100 psig above ambient and testing was repeated.

5. Results

5.1 Test Conditions

Supply pressure to the EX-1 was set under static conditions at the start of each run at depth. Two complete tests were conducted, the first using a statically preset supply pressure of 50 psig above ambient and second using 100 psig above ambient. The supply gas was provided from the Experimental Diving Facility's field of air bottles via approximately 100 feet of piping and several open isolation valves.

Under normal conditions the air field is pressured above 2000 psig. However, mechanical failure of the Experimental Diving Facility's high pressure air compressor had allowed the field's air pressure to drop to 1200 psig at the start of the EX-1's testing. An estimated 14,700 cubic feet of air were used during testing, and by the end of the

final run, air field supply pressure had dropped to 600 psig. During high breathing rates the volume of gas supplied by the field was insufficient due to the very low driving head, and line losses. This had a severe effect on regulated supply pressure to the EX-1 MOD 0. During the May 1984 testing of the EX-1 MOD 1, the diving facility's air field pressure was maintained in excess of 2000 psig.

5.2 Test Results

5.2.1 Manned Testing (Dry)

Manned bench testing in January 1984 of the EX-1 MOD 0 by the author (manual breathing of the unit) immediately identified gas leakage problems with the poppet valve and its seat. After lapping of the original stainless steel valve and seat, leakage remained severe. A modified poppet valve and seat, using an O-ring to provide compliant seating was tried (Figure 4). Leaking continued unless a closure force in excess of one pound was used. Since the EX-1 does not incorporate a mechanical advantage for opening the poppet valve, diver inhalation could not overcome such a large closure force. Ultimately, a compromise set up, using light spring shutting force (approximately 1-1/2 oz.) and moderate gas leakage (approximately 8 LPM) was utilized. This provided low breathing effort when the EX-1 MOD 0 was breathed manually.

During manned testing another problem was identified. As inhalation gas entered the breathing bowl it impinged on the three-inch diaphragm. Additionally, high gas flow over the O-ring of the poppet valve created a downstream force, tending to close the poppet. Oscillations resulted since these flow related forces tended to close the valve while the differential pressure caused during inhalation tended to open the valve. At high breathing rates these oscillations became severe, making the regulator's operation very uncomfortable. Two steps were taken to correct these problems. First, a deflector cap was installed over the valve seat/valve opening, directing flow away from the three-inch diaphragm and toward the diver's mouthpiece. Second, gas supply pressure to the EX-1 MOD 0 was set at or below 100 psig above ambient. This reduced the gas flow velocity over the O-ring surface, reducing the aerodynamic closure force. (Also, gas supply pressures to the EX-1 MOD 0 in excess of 125 psig above ambient caused the O-ring to blow-out of the O-ring seat, resulting in uncontrolled gas flow to the diver.) By adding the deflector cap and reducing gas supply pressure to the EX-1 MOD 0, the unit's instability was reduced to a comfortable level and the O-ring remained in place.

Manned testing of the EX-1 MOD 1 in May 1984 revealed that the new knife edge poppet valve and compliant rubber seat had stopped gas leakage. A gas deflector was still needed to prevent gas impingement onto the three-inch diaphragm.

5.2.2 Unmanned Testing (Wet)

5.2.2.1 EX-1 MOD 0

The EX-1 MOD 0 was tested twice during January, using a breathing machine, and was mechanically identical for both tests. The two tests, using 50 psig and 100 psig above ambient supply pressures, demonstrated that the EX-1 met the Navy's work-of-breathing performance goal of less than 0.18 kg-m/l at 62.5 LPM, 132 fsw. Figures 6 and 7 are plots of depth versus work-of-breathing for 50 psig and 100 psig above ambient supply pressures, respectively. Both figures show that work-of-breathing generally increased as depth and/or breathing rate increase.

The EX-1's performance remained generally consistent for both 50 psig and 100 psig above ambient supply pressures. Higher breathing rates were obtainable using a 100 psig above ambient supply since the gas volume available to the EX-1 MOD 0 was theoretically twice the volume provided by the 50 psig above ambient supply. The Navy's work-of-breathing performance goals were met, and the Ex-1's breathing work performance was comparable to the U.S. Diver's Conshelf XIV and the Scubapro Air I demand regulators. The Conshelf XIV and Air I are classified by the Navy as two of the best demand regulators available (Reference 1).

Figure 6 Depth vs Work-of-Breathing

50 psig Supply Pressure

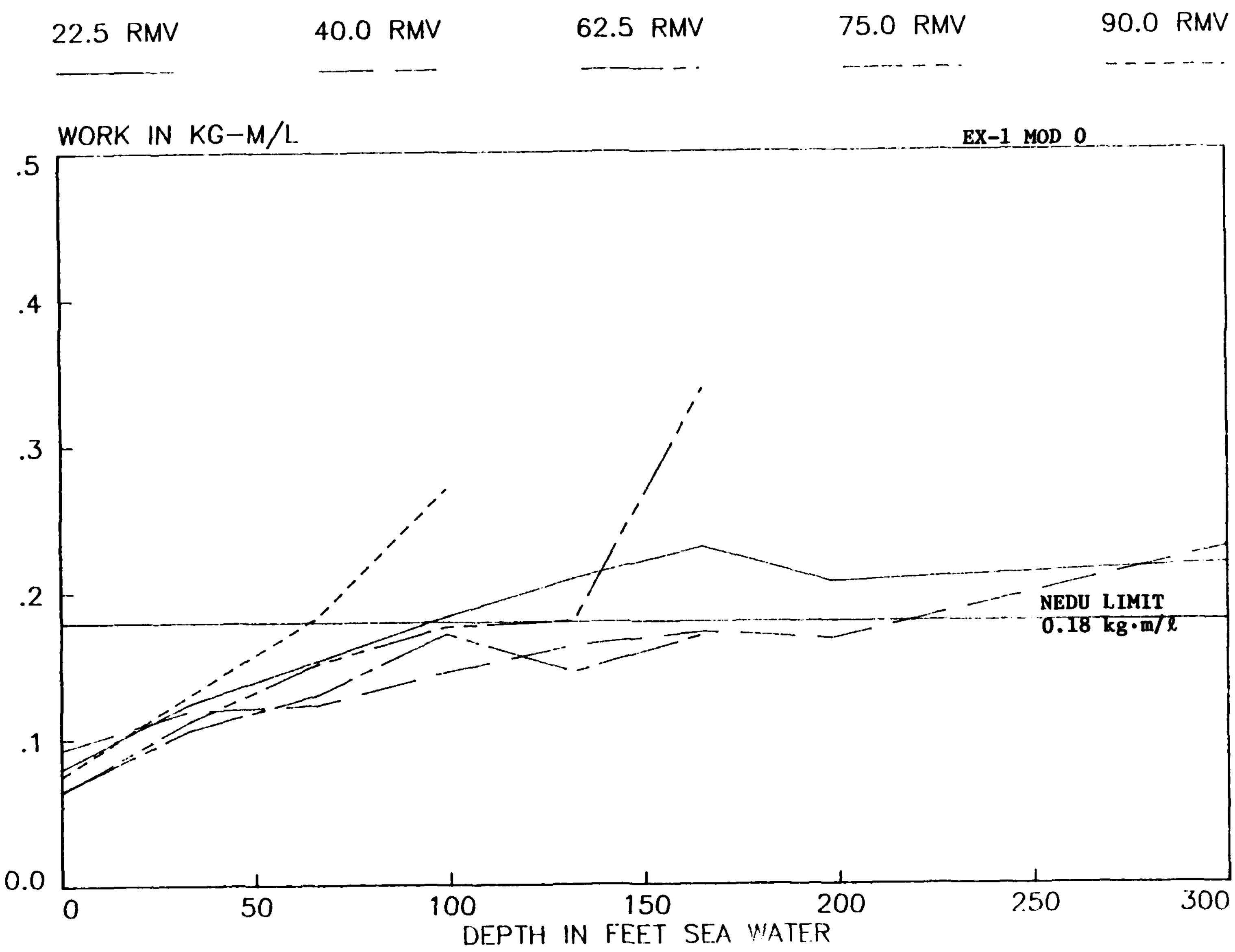


Figure 7 Depth vs Work-of-Breathing

100 psig Supply Pressure

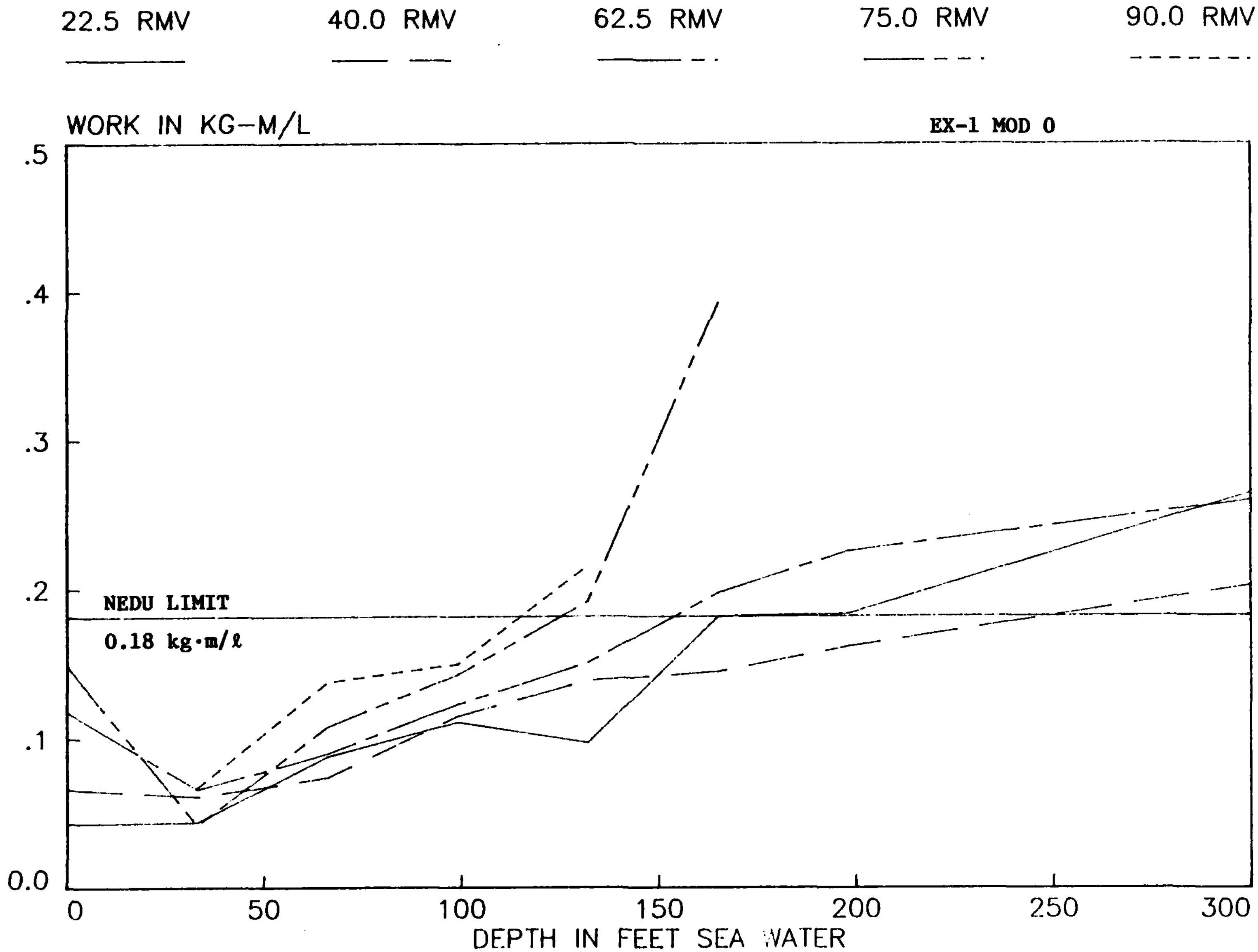


Figure 8a Peak Exhalation/Inhalation Pressure (cmH20)

for 22.5 RMV

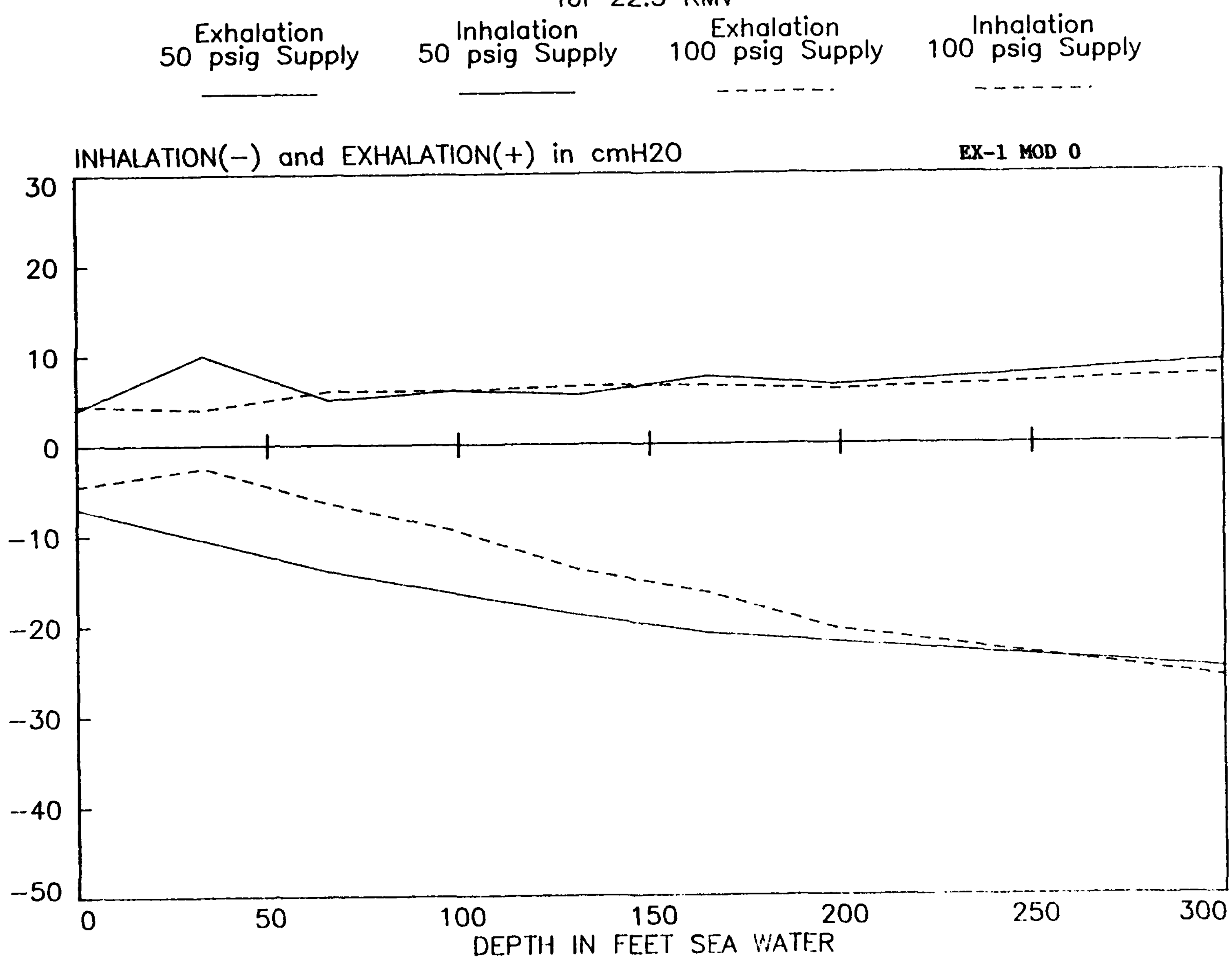


Figure 8b Peak Exhalation/Inhalation Pressure (cmH2O)

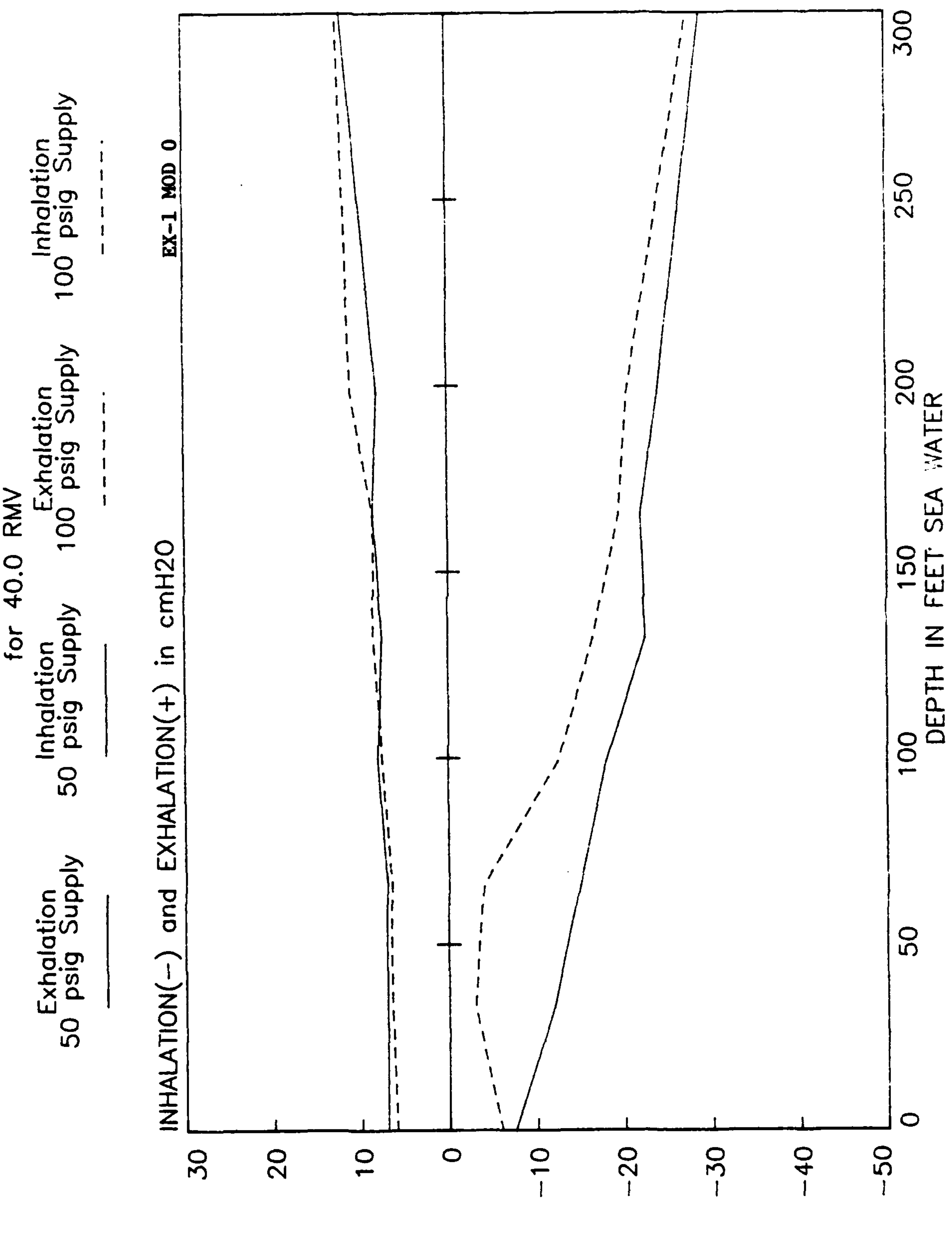


Figure 8c Peak Exhalation/Inhalation Pressure (cmH20)

for 62.5 RMV

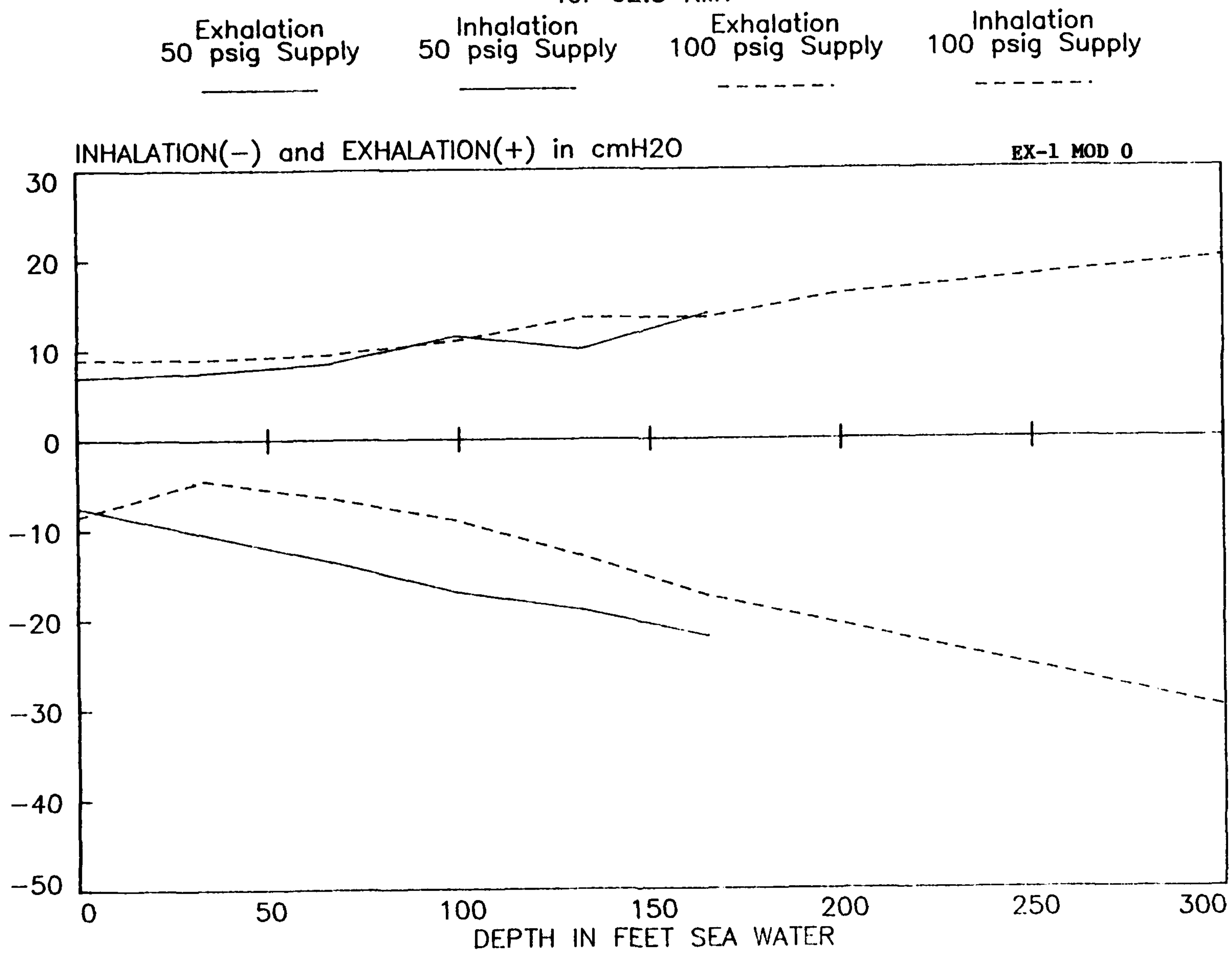


Figure 8d Peak Exhalation/Inhalation Pressure (cmH20)

for 75.0 RMV

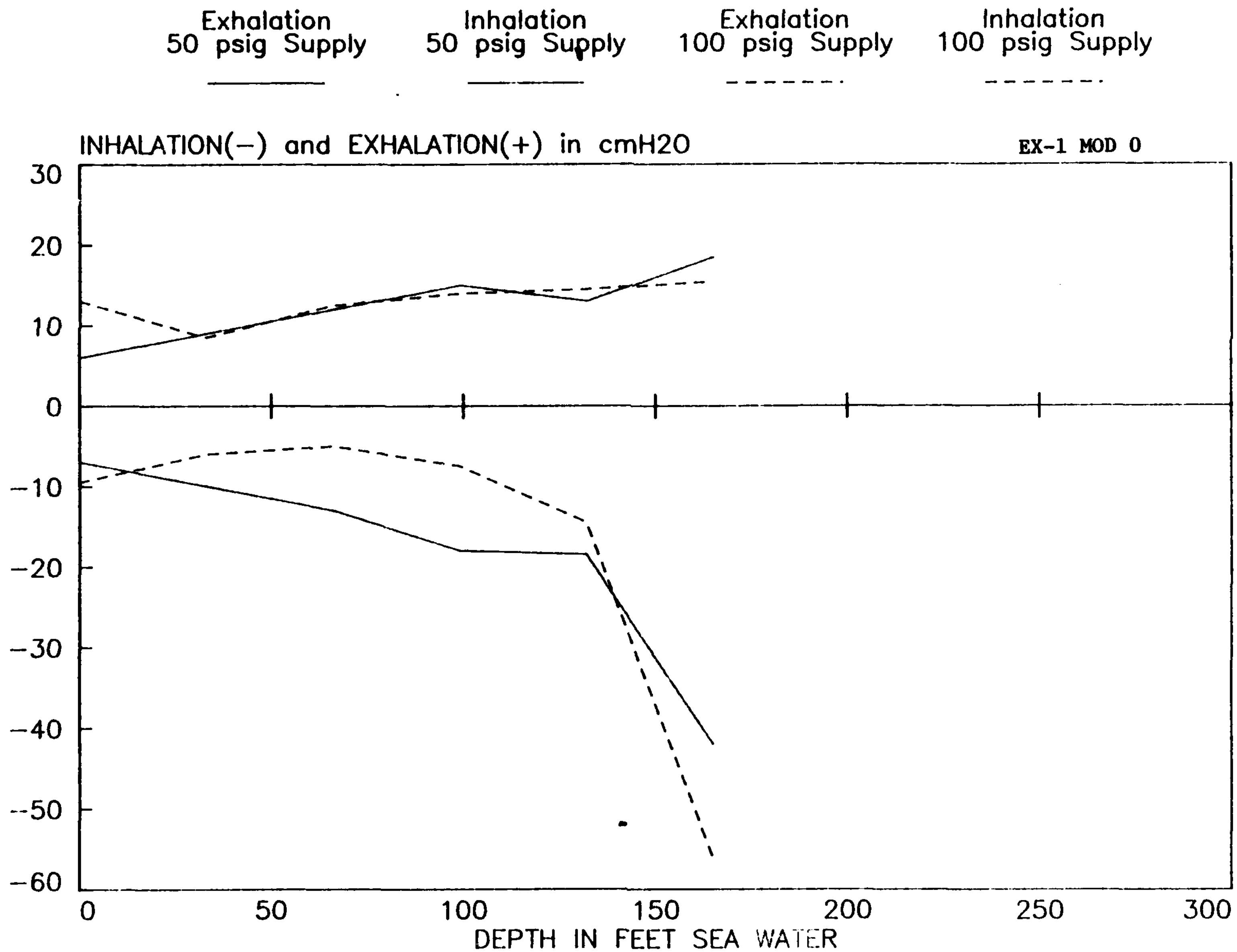
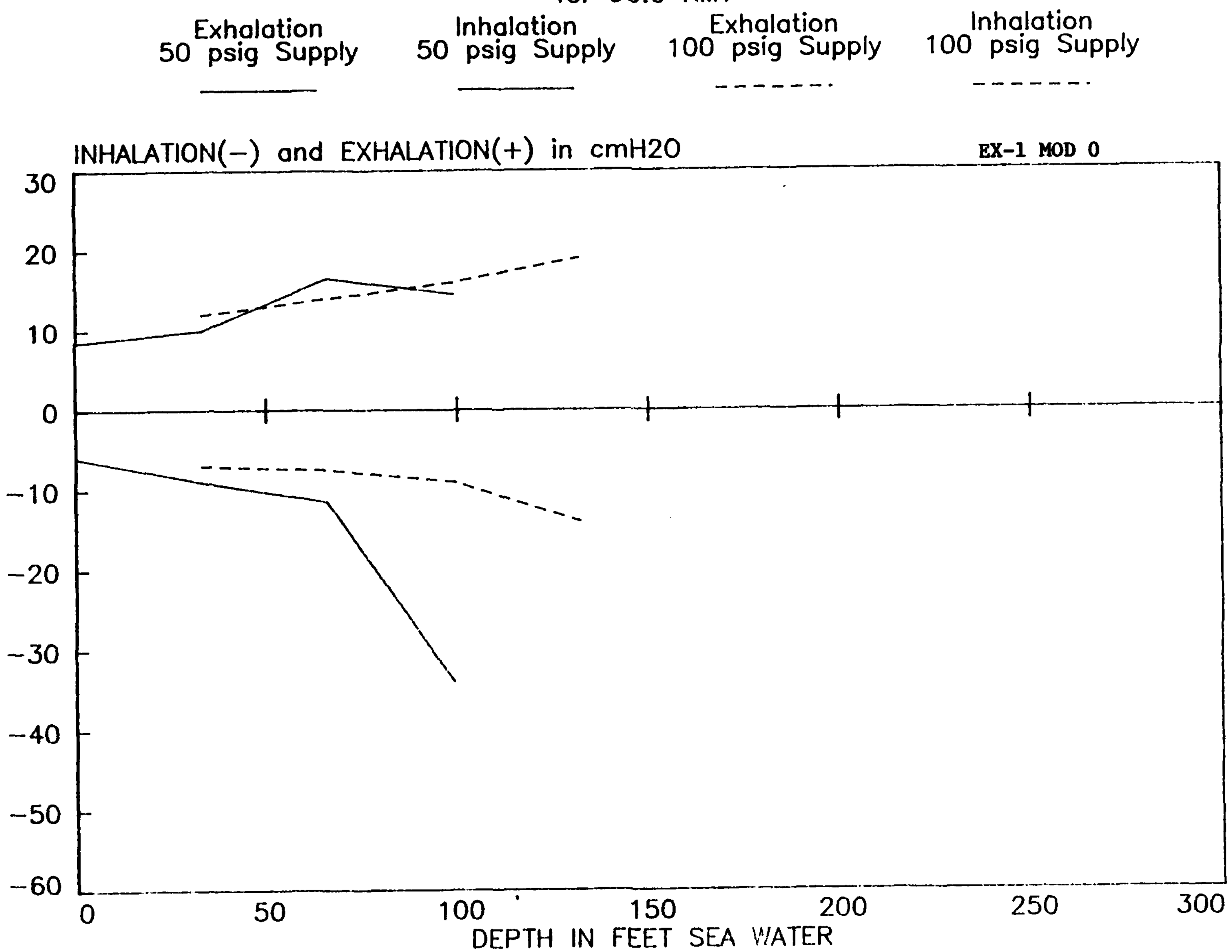


Figure 8e Peak Exhalation/Inhalation Pressure (cmH20)

for 90.0 RMV



While the EX-1 MOD 0 was able to meet the Navy's work-of-breathing goals, Figures 8a through 8e are plots showing that peak inhalation pressures were often excessively high. The most severe peak was 56 cm H_2O, was recorded during operation at 75.0 LPM at 165 fsw using a supply pressure of 100 psig above ambient. In general, high peak inhalation pressures increased as depth increased. Peak inhalation pressures in excess of 20 cm H_2O generally occurred at depths greater than 132 fsw.

The air field's low supply pressure resulted in large line pressure losses to the EX-1. Figures 9 and 10 show that these losses increased with depth and/or breathing rate. These losses were as high as 33.6 psig for a 50 psig supply (a 67.2% loss) and 52.8 psig for a 100 psig supply (a 52.8% loss). While the EX-1's balanced poppet valve reduced the effect of gas supply pressure drops, fluctuations in excess of 50% were not anticipated. In spite of these severe drops in supply pressure, Figures 6 and 7 show that the EX-1 MOD 0 was still able to operate at 40 LPM at 300 fsw with a 50 psig gas supply pressure and at 62.5 LPM at 300 fsw with a 100 psig gas supply pressure.

In several cases of high breathing rates, the EX-1 MOD 0 produced a positive differential pressure in the breathing bowl during inhalation. This was a result of regulator gas flow exceeding demand. If this positive pressure is too large, gas is literally forced to the diver and discomfort results

Figure 9 Line Pressure Loss

50 psig Supply Pressure

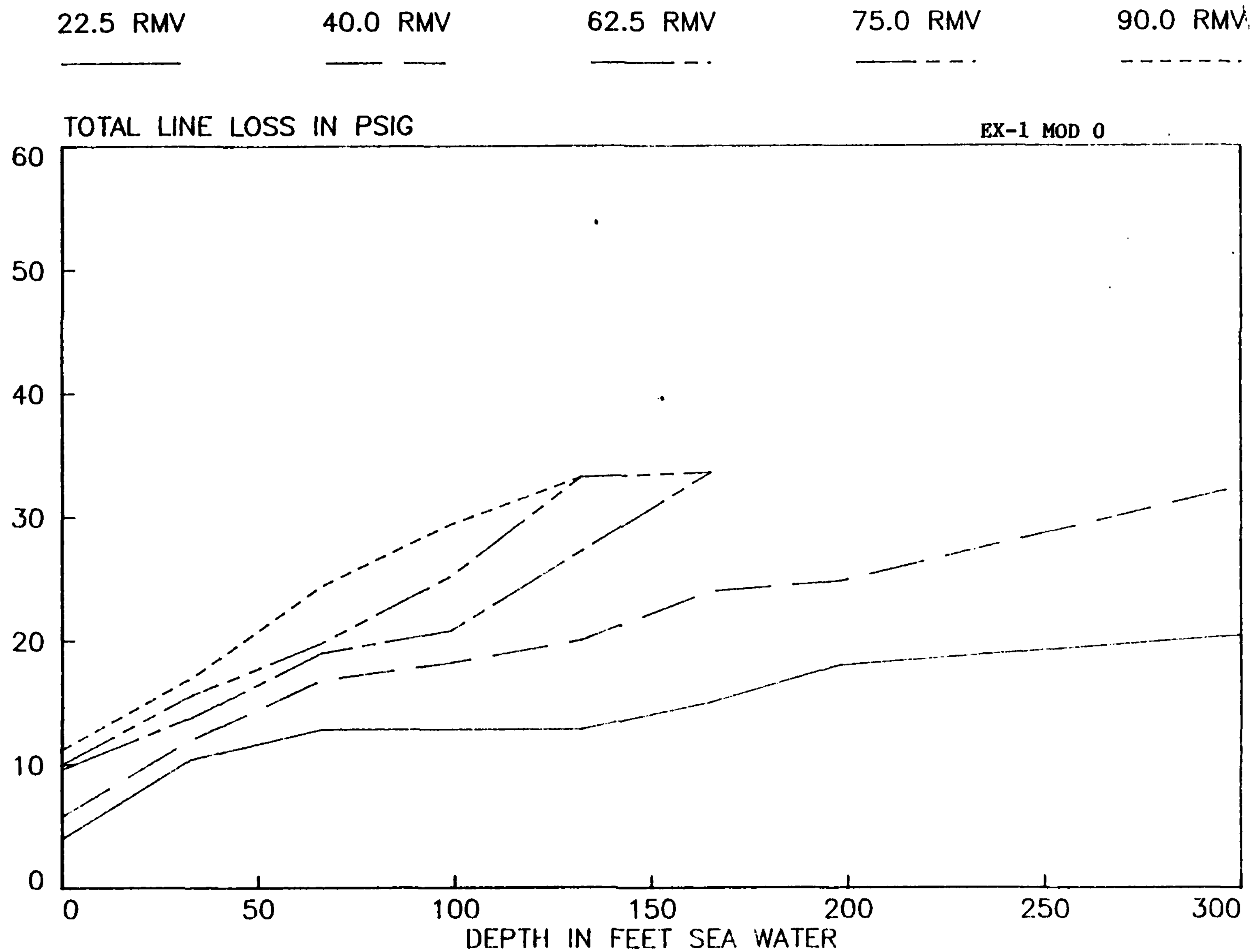
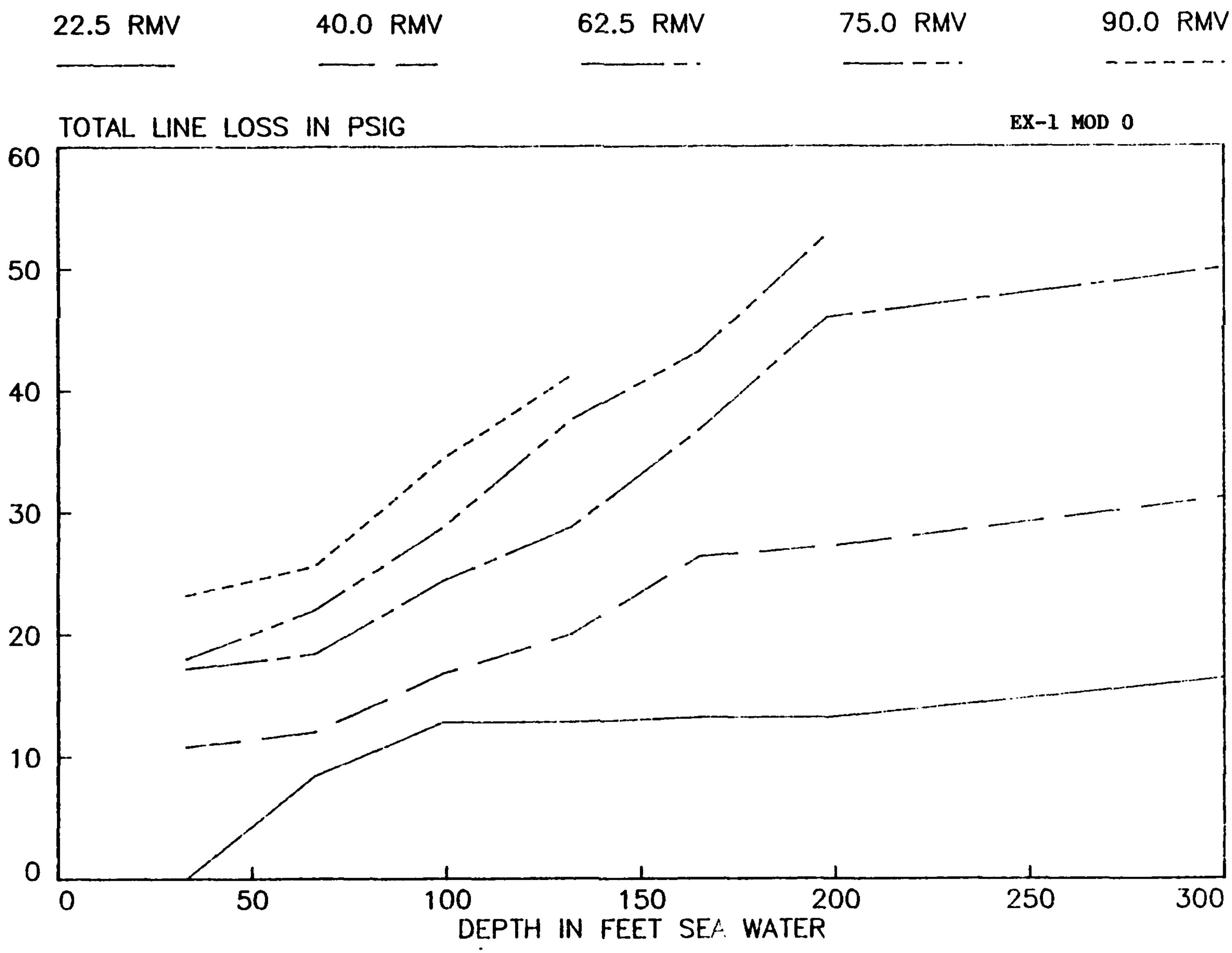


Figure 10 Line Pressure Loss

100 psig Supply Pressure



The EX-1 MOD 0's poppet valve and seat continued to leak throughout the testing. The leak rate was estimated at less than 8 LPM. While this leak rate would be considered excessive for a production unit, it did not adversely effect testing of the prototype.

Despite its drawbacks, the EX-1 MOD 0 performed very well. Reference 1 shows that most open-circuit demand regulators cannot be tested above 40 LPM at 300 fsw. The EX-1 exhibited a work-of-breathing of 0.260 kg-m/l at 62.5 LPM, 300 fsw with a 100 psig gas supply pressure. This work-of-breathing was in excess of NEDU goals but not unreasonably so.

Based on the test results, the EX-1 MOD 0 displayed the ability to continuously operate, while meeting Navy performance goals, in spite of large dynamic gas supply pressure losses. These were the design goals for the EX-1.

5.2.2.2 EX-1 MOD 1

The EX-1 MOD 1 was tested on 2 May 1984 in accordance with Appendix C. Its new poppet valve and compliant seat eliminated gas leakage and improved overall performance. By comparing Figures 11 and 12 (EX-1 MOD 1 breathing work) with Figures 6 and 7 (EX-1 MOD 0 breathing work) it is seen that the MOD 1 performed much better than the MOD 0.

Figure 11 Depth vs Work-of-Breathing (Mod 1)

50 psig Supply Pressure

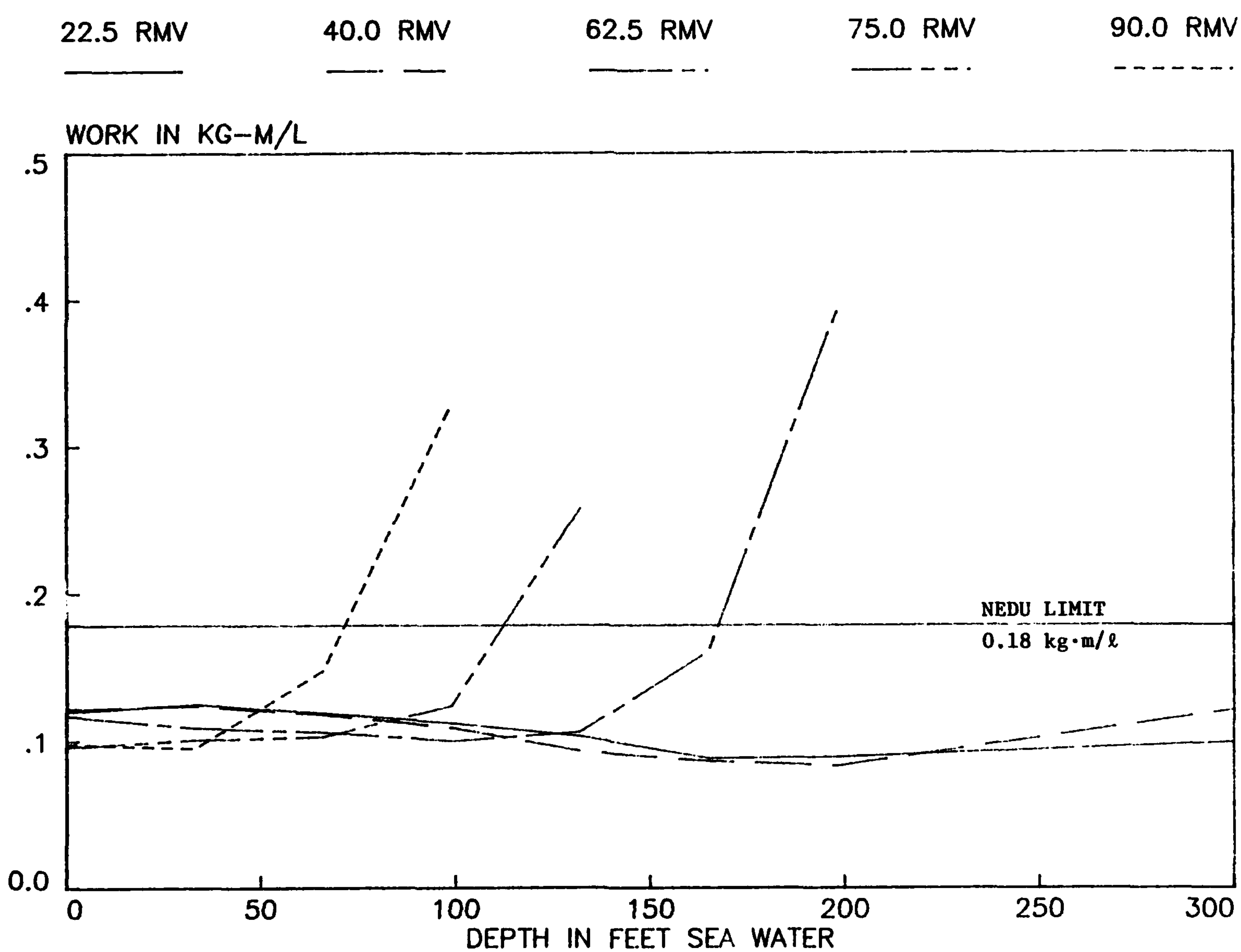
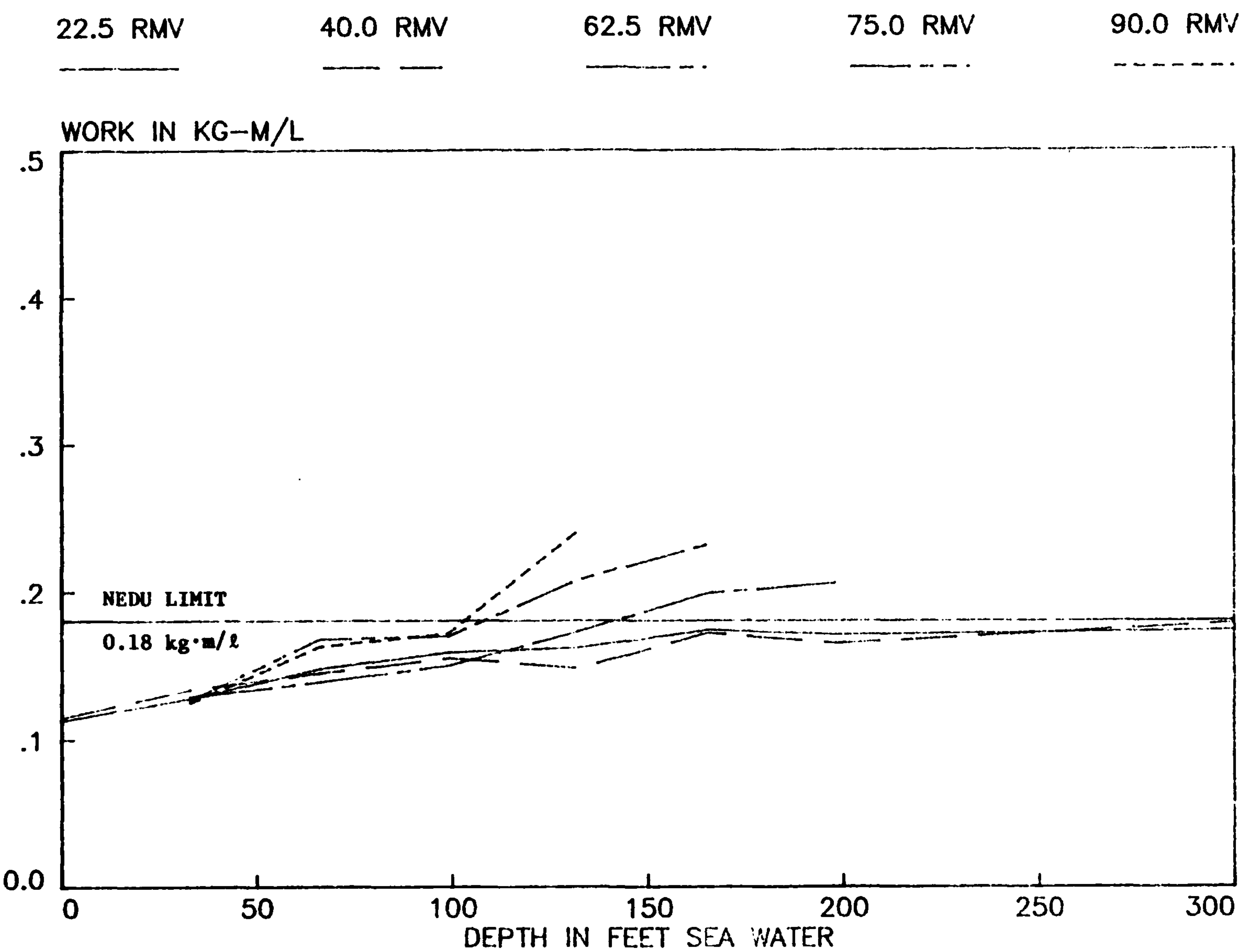


Figure 12 Depth vs Work-of-Breathing (Mod 1)

80 psig Supply Pressure



5.3 Performance Problems

As with most first-generation prototypes, the EX-1 experienced several problems. The most obvious of these was the gas leakage from the poppet valve and seat assembly used in the EX-1 MOD 0.

Initially, the valve and seat assembly were made of stainless steel (Figure 4). This combination displayed unacceptable gas leakage even after lapping. Prior to unmanned testing a new poppet valve and seat assembly utilizing an O-ring were installed (EX-1 MOD 0). This assembly still leaked gas but the leak rate was reduced to approximately 8 LPM.

Gas flow past the poppet valve and its seat created downstream aerodynamic force as a result of the O-ring surface on the seating edge of the poppet valve (Figure 4). This force opposed the three-inch diaphragm's opening force, tending to close the poppet valve. Higher gas flows across the poppet valve and seat created greater aerodynamic forces.

During the opening portion of the poppet valve's operating cycle, gas passages are smallest. Given the EX-1 MOD 0's leak rate of 8 LPM, large flow velocities occurred during opening and closing. As a result, the largest aerodynamic forces occurred at these points of operation. As regulator depth increased, gas pressures and gas density increased proportionally. Higher gas density at greater depths increased the aerodynamic force which was

counteracted by a larger opening force, which in turn required a larger inhalation effort. Thus high-peak inhalation pressures occurred as depth and breathing rate increased. This problem was corrected in the EX-1 MOD 1 by installing a new poppet valve and seat basin.

Due to the elimination of virtually all friction, oscillations of the poppet valve occurred during manned and unmanned testing for both the EX-1 MOD 0 and MOD 1. Damping of these oscillations was achieved, with moderate success, by restricting the size of the gas flow passages between the breathing bowl and the three-inch diaphragm. These oscillations may have been a result of dynamic forces acting on the poppet valve face and/or the three-inch diaphragm. However, since quasi-steady flow was assumed during modeling and analysis of the EX-1, dynamic forces were neglected. To determine the source and magnitude of the major dynamic forces at work in the EX-1, additional detailed mathematical analysis is required.

As regulator depth and breathing rates increased, the EX-1's operational limits were exceeded due to an insufficient volume of supply gas. The EX-1's poppet valve and its seat provided an 0.310-inch diameter hole for the high pressure gas to enter the breathing bowl. To supply an adequate volume of gas to the diver with a gas supply pressure of 50 psig above ambient, the poppet valve had to lift approximately 0.050 inches off its seat (Appendix A).

However, since gas supply pressure dropped dynamically with demand the poppet valve had to lift further to supply the same volume of gas. Eventually, the gas supply volume could not meet demand. The plots in Figures 6, 7, 11 and 12 graphically show the effects of inadequate gas supply, and the inability to conduct testing when this occurred.

6. Reliability and Maintainability

6.1 Steps Taken to Improve Reliability and Maintainability

The EX-1 was designed to be simple, reliable, and maintainable. The cross-sectional view of Figure 3 shows that the EX-1 consists of few moving parts. Frictional losses were reduced and gas/water sealing was accomplished by using a rolling diaphragm. Reliability of the EX-1 was prompted by minimizing poppet valve travel and complexity of the mechanism. Additionally, commercially proven components such as the three-inch diaphragm, the silicon exhalation check valve, the rolling diaphragm and the stainless steel compression spring were used. The prototype EX-1 is easily maintained, by design. The unit can be disassembled into its basic components with a flathead screwdriver and an allen wrench, allowing for easy repair/replacement of all components.

6.2 Potential Problems

The greatest problem with the prototype EX-1 MOD 0 is the poppet valve and seat. The O-ring installation in the

poppet valve, as shown in Figure 4, has several problems. First, this configuration leaked. Second, gas flow over the seating surface and O-ring affected performance and high gas flow tended to lift the O-ring from its groove, causing valve failure. Finally, the EX-1 MOD 1 eliminated the aerodynamic forces associated with the O-ring seat of the MOD 0, but large poppet valve oscillations can still occur. If these oscillations become too severe unstable gas flow to the diver could result in severe breathing discomfort or personal injury.

6.3 Future Design Suggestions

Several major changes could improve the EX-1. First is the redesign of the EX-1 poppet valve and seat assembly, improving the EX-1 MOD 1 design by reversing placement of the knife edge and seat, as shown in Figure 13. Second, a simple lever system could be used to open the valve, reducing diver inhalation effort. Third, the enclosure of the spring system within the regulator body (Figure 13) would reduce the length and weight of the EX-1 and minimize the possibility of spring corrosion from sea water. Ultimately, a more detailed engineering analysis of the EX-1 is needed to identify the dynamic forces at work in the regulator.

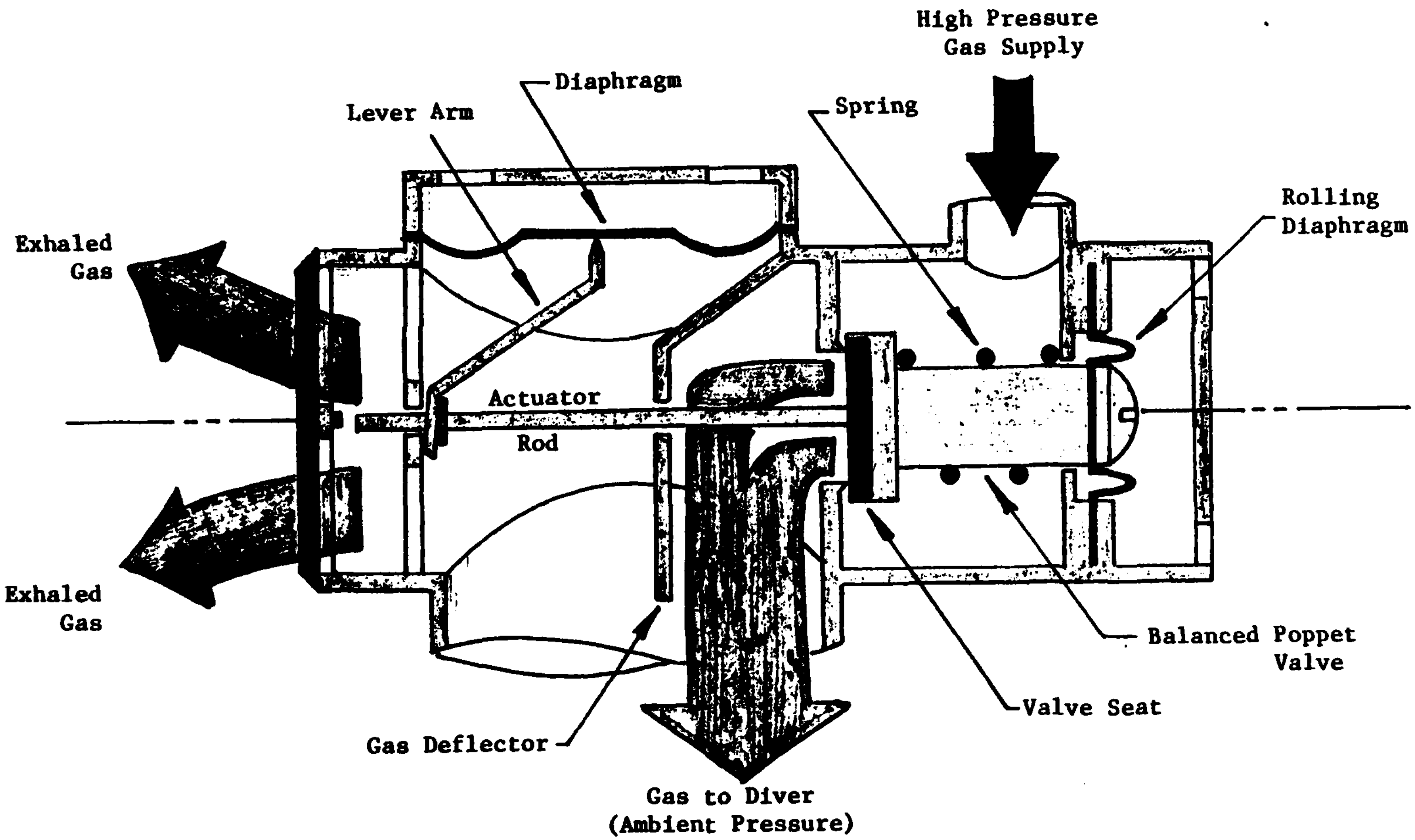


FIGURE 13. EX-1 FUTURE DESIGN

APPENDIX A1

Mathematical Model

The mathematical model for EX-1 was developed during the early design phase. A sinusoidal breathing pattern was assumed with inhalation and exhalation durations equal. For the fastest breathing rate of Appendix B, thirty breaths per minute, one inhalation lasts for one second. Because the poppet valve, actuator rod and spring were designed to be relatively small masses and poppet valve travel duration is one second or greater, quasi-steady flow conditions were assumed.

The mathematical model treats the gas flow passage between the poppet valve and its seat as an orifice. Having assumed a sinusoidal breathing pattern and using Reference 2 for the flow of compressible fluids through orifices, equation one was developed.

$$d = \left| \frac{7.51 \times 10^{-4}\ RMV}{\left(\frac{P}{(.44D+14.7)}\right) T^{1/2} r} \right| \pi \sin(wt) \qquad (1)$$

where: d - poppet valve motion wrt the valve seat (inches)

$w - \frac{\pi\ BR}{30}$

BR - breathing rate (breaths per minute)

RMV - respiratory minute volume (liters per minute)

P - regulator's gas supply pressure wrt ambient pressure at depth (psig)

D - depth (ft)

T - ambient temperature at depth (°R)

r - poppet valve radius (inches)

This equation describes the motion of the EX-1's poppet valve with respect to its seat as a function of time, valve geometry and diving conditions.

Since the poppet valve is balanced with respect to gas supply pressure, forces acting on the valve are a function of breathing bowl pressure, the compression spring and sliding friction. At steady state, neglecting friction, the sum of these forces must be zero, providing equation two.

$$\Sigma F = 0 = A_e (Pa - P) - F_s + kd \tag{2}$$

where: A_e - effective piston area of the breathing bowl diaphragm (inches)

Pa - ambient pressure (psig)

P - breathing bowl pressure (psig)

F_s - spring pre-load (closing) force (LBF)

k - spring constant (LBF/inch)

d - poppet valve travel wrt its seat (inches)

Working with equation one and two, the mathematical model ultimately yields equation three, which calculates breathing bowl differential pressure as a function of time, valve geometry and diving conditions. Breathing bowl differential pressure is a direct indication of the effort a diver must exert to breathe. So, by changing variables within the mathematical model it was

possible to obtain a theoretical evaluation of the EX-1.

$$(Pa - P) = \frac{F_s + kd}{(\frac{D^2}{4} - r^2)} \qquad (3)$$

where: (Pa-P) - breathing bowl differential pressu (psig)

F_s - spring pre-load (closing) force (LBF)

k - spring constant (LBF/inch)

d - poppet valve travel wrt its seat (inches)

D - large diaphragm effective piston diameter (inches)

r - poppet valve radius (inches)

APPENDIX A2

COMPUTER PROGRAM

```
C
C       PROGRAM FOR EVALUATION OF THE EX-1
C
C       READ IN THE TEMPERATURE, DEPTH, SPOOL VALVE DIAMETER,
C       DIAPHRAM DIAMETER, RMV, BPM AND OVERBOTTOM PRESSURE
C
        REAL KSPR,NUM
        PRINT*,'WHAT OUTPUT FILE IS TO BE USED?'
        READ*,OUT
        PRINT*,'INPUT: TEMPERATURE OF THE WATER IN RANKINE.'
        READ*,TEMP
        PRINT*,'INPUT: DIAMETER OF THE SPOOL VALVE IN INCHES.'
        READ*,VD
 11     PRINT*,'INPUT: DIAMETER OF THE DIAPHRAM IN INCHES.'
        READ*,D
        IF(IANS1.EQ.1) GOTO 18
 22     PRINT*,'INPUT: OVERBOTTOM PRESSURE IN PSIG.'
        READ*,OBPRES
        IF(IANS1.EQ.1) GOTO 18
 33     PRINT*,'INPUT: DIVER DEPTH IN FEET SEA WATER.'
        READ*,DEPTH
        PRINT*,'INPUT: 1) FRICTION FORCE, FO    2) PRESET SPRING FORCE,
        1 F1S    3) SPRING CONSTANT, KSPR'
        READ*,FO,PREFOR,SPRING
        IF(IANS1.EQ.1) GOTO 18
 44     PRINT*,'INPUT: RMV (LPM) AND BREATHING RATE (BPM).'
        READ*,RMV,BPM
        IF(IANS1.EQ.1) GOTO 18
C
C       PRINT OUT VALUES
C
 90     WRITE(OUT,60) ' TEMPERATURE =', TEMP,' deg R'
        WRITE(OUT,60) ' VALVE DIAMETER =',VD,' inches'
        WRITE(OUT,60) ' DIAPHRAM DIAMETER =',D,' inches'
        WRITE(OUT,60) ' OVER BOTTOM PRESSURE =',OBPRES,' psi'
        WRITE(OUT,60) ' DIVER DEPTH =',DEPTH,' feet sea water'
        WRITE(OUT,60) ' RMV =',RMV,' liters/min'
        WRITE(OUT,60) ' BPM =',BPM,' breaths/min'
        PI=3.1415926
        T2=30./BPM
        T4=T2/2.
        FOL=FO
        W=PI*BPM/30.
        R=VD/2.
        NUM=(7.504)*(10.**(-4))*RMV
        DENOM=R*(TEMP**.5)*(1.+OBPRES/(.44*DEPTH+14.7))
        DAVE=NUM/DENOM
C
C       LOOPS: FO = FRICTION FORCE   F1S = PRESET SPRING FORCE
C              KSPR = SPRING CONSTANT
C
        F1S=PREFOR
        KSPR=SPRING
        WRITE(OUT,20) ' ****************NEW RUN****************'
        WRITE(OUT,21)' FO=',FO,'    F1S=',F1S,'    KSPR=',KSPR
        WRITE(OUT,20)'     TIME sec      d(t) inches     (Pa-P(t))
        1 lbf/sqin'
        DO 100 I=1,21
               T=T2*(I-1)/20.
               IF(T.GT.T4) FOL=-FO
```

```
                DT=DAVE*PI*SIN(W*T)
                PAP=(FOL+F1S+KSPR*DT)/(PI*(D**2/4.-R**2))
                WRITE(OUT,10) T,DT,PAP
                WRITE(22,19) T,DT
                WRITE(23,19) T,PAP
                WRITE(24,19) DT,PAP
100     CONTINUE
10      FORMAT(F10.3,F15.4,F20.4)
19      FORMAT(2E15.8)
21      FORMAT(3(A,F8.5))
20      FORMAT(A)
60      FORMAT(A,F10.4,A)
        PRINT*,'DO YOU WISH TO CHANGE ANY PARAMETERS?  YES=1, NO=0'
        READ*, IANS1
        IF(IANS1) 59,59,57
57      PRINT*,'WHICH PARAMETER?'
        PRINT*,'DIAPHRAM = 1'
        PRINT*,'OVER BOTTOM PRESSURE = 2'
        PRINT*,'DEPTH = 3'
        PRINT*,'RMV,BPM = 4'
        READ*, IANS2
        IF(IANS2.EQ.1) GOTO 11
        IF(IANS2.EQ.2) GOTO 22
        IF(IANS2.EQ.3) GOTO 33
        IF(IANS2.EQ.4) GOTO 44
18      PRINT*,'DO YOU WANT TO CHANGE ANYTHING ELSE? YES=1, NO=0'
        READ*, IANS3
        IF(IANS3.EQ.1) GOTO 57
        IF(IANS1.EQ.1) GOTO 90
59      STOP
        END
```

APPENDIX A3

COMPUTER RESULTS

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 50.0000 psi
DIVER DEPTH = 0.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0021	0.0348
0.100	0.0042	0.0369
0.150	0.0061	0.0390
0.200	0.0079	0.0408
0.250	0.0096	0.0425
0.300	0.0109	0.0439
0.350	0.0120	0.0451
0.400	0.0128	0.0459
0.450	0.0133	0.0464
0.500	0.0135	0.0466
0.550	0.0133	0.0464
0.600	0.0128	0.0459
0.650	0.0120	0.0451
0.700	0.0109	0.0439
0.750	0.0096	0.0425
0.800	0.0079	0.0408
0.850	0.0061	0.0390
0.900	0.0042	0.0369
0.950	0.0021	0.0348
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 50.0000 psi
DIVER DEPTH = 100.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0050	0.0378
0.100	0.0099	0.0429
0.150	0.0146	0.0477
0.200	0.0189	0.0521
0.250	0.0227	0.0561
0.300	0.0260	0.0595
0.350	0.0286	0.0622
0.400	0.0305	0.0642
0.450	0.0317	0.0654
0.500	0.0321	0.0658
0.550	0.0317	0.0654
0.600	0.0305	0.0642
0.650	0.0286	0.0622
0.700	0.0260	0.0595
0.750	0.0227	0.0561
0.800	0.0189	0.0521
0.850	0.0146	0.0477
0.900	0.0099	0.0429

0.950	0.0050	0.0378
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 50.0000 psi
DIVER DEPTH = 200.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
*****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0063	0.0391
0.100	0.0124	0.0454
0.150	0.0182	0.0514
0.200	0.0235	0.0569
0.250	0.0283	0.0618
0.300	0.0324	0.0661
0.350	0.0356	0.0695
0.400	0.0380	0.0719
0.450	0.0395	0.0735
0.500	0.0400	0.0740
0.550	0.0395	0.0735
0.600	0.0380	0.0719
0.650	0.0356	0.0695
0.700	0.0324	0.0661
0.750	0.0283	0.0618
0.800	0.0235	0.0569
0.850	0.0182	0.0514
0.900	0.0124	0.0454
0.950	0.0063	0.0391
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 50.0000 psi
DIVER DEPTH = 300.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
*****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0069	0.0398
0.100	0.0137	0.0468
0.150	0.0201	0.0534
0.200	0.0261	0.0596
0.250	0.0314	0.0650
0.300	0.0359	0.0697
0.350	0.0395	0.0735
0.400	0.0422	0.0762
0.450	0.0438	0.0779
0.500	0.0443	0.0785
0.550	0.0438	0.0779
0.600	0.0422	0.0762
0.650	0.0395	0.0735
0.700	0.0359	0.0697
0.750	0.0314	0.0650
0.800	0.0261	0.0596

0.850	0.0201	0.0534
0.900	0.0137	0.0468
0.950	0.0069	0.0398
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 100.0000 psi
DIVER DEPTH = 0.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
*****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0012	0.0338
0.100	0.0024	0.0350
0.150	0.0035	0.0362
0.200	0.0045	0.0372
0.250	0.0054	0.0382
0.300	0.0062	0.0390
0.350	0.0068	0.0396
0.400	0.0072	0.0401
0.450	0.0075	0.0404
0.500	0.0076	0.0405
0.550	0.0075	0.0404
0.600	0.0072	0.0401
0.650	0.0068	0.0396
0.700	0.0062	0.0390
0.750	0.0054	0.0382
0.800	0.0045	0.0372
0.850	0.0035	0.0362
0.900	0.0024	0.0350
0.950	0.0012	0.0338
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 100.0000 psi
DIVER DEPTH = 100.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
*****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0034	0.0362
0.100	0.0068	0.0396
0.150	0.0100	0.0429
0.200	0.0129	0.0460
0.250	0.0156	0.0487
0.300	0.0178	0.0510
0.350	0.0196	0.0529
0.400	0.0209	0.0542
0.450	0.0217	0.0551
0.500	0.0220	0.0554
0.550	0.0217	0.0551
0.600	0.0209	0.0542
0.650	0.0196	0.0529
0.700	0.0178	0.0510
0.750	0.0156	0.0487
0.800	0.0129	0.0460
0.850	0.0100	0.0429
0.900	0.0068	0.0396

0.950	0.0034	0.0362
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 100.0000 psi
DIVER DEPTH = 200.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
*****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0047	0.0375
0.100	0.0093	0.0422
0.150	0.0137	0.0468
0.200	0.0177	0.0509
0.250	0.0213	0.0546
0.300	0.0244	0.0578
0.350	0.0268	0.0604
0.400	0.0287	0.0622
0.450	0.0298	0.0634
0.500	0.0301	0.0638
0.550	0.0298	0.0634
0.600	0.0287	0.0622
0.650	0.0268	0.0604
0.700	0.0244	0.0578
0.750	0.0213	0.0546
0.800	0.0177	0.0509
0.850	0.0137	0.0468
0.900	0.0093	0.0422
0.950	0.0047	0.0375
1.000	0.0000	0.0326

TEMPERATURE = 530.0000 deg R
VALVE DIAMETER = 0.3100 inches
DIAPHRAM DIAMETER = 2.0000 inches
OVER BOTTOM PRESSURE = 100.0000 psi
DIVER DEPTH = 300.0000 feet sea water
RMV = 90.0000 liters/min
BPM = 30.0000 breaths/min
*****************NEW RUN****************
FO= 0.00000 F1S= 0.10000 KSPR= 3.17000

TIME sec	d(t) inches	(Pa-P(t)) lbf/sqin
0.000	0.0000	0.0326
0.050	0.0055	0.0383
0.100	0.0109	0.0439
0.150	0.0161	0.0492
0.200	0.0208	0.0541
0.250	0.0250	0.0585
0.300	0.0286	0.0622
0.350	0.0315	0.0652
0.400	0.0336	0.0674
0.450	0.0349	0.0687
0.500	0.0354	0.0692
0.550	0.0349	0.0687
0.600	0.0336	0.0674
0.650	0.0315	0.0652
0.700	0.0286	0.0622
0.750	0.0250	0.0585
0.800	0.0208	0.0541

0.850	0.0161	0.0492
0.900	0.0109	0.0439
0.950	0.0055	0.0383
1.000	0.0000	0.0326

APPENDIX B

NAVY EXPERIMENTAL DIVING UNIT

REPORT 3-81

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407

IN REPLY REFER TO:

NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 3-81

STANDARDIZED NEDU UNMANNED UBA TEST PROCEDURES AND PERFORMANCE GOALS

JAMES R. MIDDLETON
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JULY 1981

AD# A105609

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Glossary

ATA	Atmospheres Absolute
°C	Degrees Centigrade
CM	Centimeters
CmH20	Centimeters of Water Pressure
CO2	Carbon Dioxide
dBA	Sound Level in Decibels ('A' Scale)
EDF	Experimental Diving Facility
°F	Degrees Farenhiet
FREQ	Frequency (Breaths Per Minute)
FSW	Feet-of-Seawater
HeO2	Helium-Oxygen Gas Mixture
Kg.M/ℓ	(Breathing Work) Kilogram Meters Per Liter of Respired Volume
ℓ	Liters
LPM	Liters Per Minute
LPS	Liters Per Second
M	Meter
MIN	Minutes
NCSC	Naval Coastal Systems Center
NEDU	Navy Experimental Diving Unit
O/B	Overbottom Pressure
P	Ambient Pressure
ΔP	Pressure Differential
ρ	Density
$\propto$	Proportional To
π	3.14
psid	Pounds Per Square Inch Differential

psig	Pounds Per Square Inch Gauge
RMV	Respiratory Minute Volume Measured in Liters Per Minute
% SEV	Percent Surface Equivalent Volume
SCUBA	Self-Contained Underwater Breathing Apparatus
STPD	Standard Temperature and Pressure
TV	Tidal Volume Measured in Liters
UBA	Underwater Breathing Apparatus
VCO2	Metabolic Carbon Dioxide Production Measured in Liters Per Minute
VO2	Metabolic Oxygen Consumption in Liters Per Minute
V Max	Maximum Flow Rate

Abstract

This report represents the most recent developments in a continuing effort by NEDU to accurately simulate the physiology of a working diver during unmanned UBA performance testing. The unmanned test procedures outlined in this document simulate the physiology of a diver performing graded exercise from light to extreme work rates. CO_2 absorbent canister duration studies duplicate the standard NEDU manned test scenario.

Performance goals are listed for all types of UBA according to their operational characteristics. These goals do not represent minimum acceptable performance levels. Rather, they are goals which when met by a piece of life support equipment, will insure that the UBA is not the limiting factor in diver performance. Acceptance of any given piece of equipment for military or commercial use must be based on specific operational requirements.

I. INTRODUCTION

The contents of this report represents the most recent developments in a continuing effort by NEDU to accurately simulate the physiology of a working diver during unmanned UBA performance tests. Use of a breathing simulator to evaluate diving life support equipment has been an accepted test method for over 20 years. However, only recently has the technology been available in manned underwater testing to evaluate all pertinant physiological parameters necessary to develop accurate unmanned test scenarios. In addition, prior performance goals for UBA's were not based on actual in-water manned tests at depth. Rather they were extrapolations from (1) scientific theory and (2) tests conducted at one atmosphere pressure.

Since 1976 extensive research and development in the above areas not only by NEDU but also the NCSC Hydrospace Laboratory in Panama City, Florida and University of New York at Buffalo has led to the formation of the unmanned test procedures and performance goals contained herein. A cross-section of the recent test reports on both manned and unmanned evaluations which led to the production of this document is given in the Reference Section. The test procedures in Section II have been found to accurately represent the physiological reactions of a diver performing graded exercise on a bicycle ergometer at levels ranging from light to extreme work. CO_2 absorbent canister duration studies duplicate the standard NEDU manned test scenario and have consistently produced comparable manned/unmanned canister bed lifes when test conditions, i.e. depth and water temperature, were similar.

The various types of UBA are broken down into 5 categories (Section III) according to their operational characteristics. Every type of diver-worn underwater breathing apparatus available either to the military or commercial diving industry is covered in one of the 5 categories. Performance goals vary with each category of equipment depending upon their breathing gas mixture, depth of operation and/or inherent state-of-the-art design limits. These performance goals have been proven reasonable in both manned and unmanned testing and have been met in each category by existing commercially available and/or military diving equipment. They do not represent minimum acceptable performance levels. Rather, they are goals which when achieved will ensure that the UBA is not a limiting factor in diver performance. Acceptance of any given piece of equipment for military or commercial use must still be based on specific operational requirements.

It is important to note that this report is meant to be a dynamic document. As technology improves and experience is gained, it will be updated to reflect any changes which will improve the unmanned test simulation or more accurately reflect reasonable UBA performance goals. In keeping with this policy of continuously updating NEDU unmanned test standards and performance goals, Appendix A contains a list of previous NEDU reports on similar subjects which are superceded by this document.

II. TEST PROCEDURES

A. Breathing Simulator Set Points and Instrumentation

Unmanned testing should be done using standardized well defined combinations of frequency (FREQ) in breaths-per-minute, tidal volume (TV), and metabolic rates ($\dot{V}O_2$) on a breathing machine. The respiratory minute volume (RMV) is simply the product TV multiplied by FREQ. The CO_2 production and O_2 consumptions are assumed to be equal and are indicative of what would be expected of subjects performing graded exercise underwater. Two basic tests are done, (1) breathing work-per-liter/inhaled CO_2 studies and (2) CO_2 absorbent canister duration studies. Table 1 lists the standardized test conditions for breathing work/inhaled CO_2 studies and, Table 2 lists standardized test conditions for CO_2 absorbent canister duration studies on closed- and semi-closed circuit UBA.

All testing should be conducted using a breathing simulator with a sinusoidal waveform and an inhalation/exhalation ratio of 1.0. A typical unmanned test setup is shown in Figure 1 with a list of instrumentation given in Table 3. Table 4 lists the address of each instrumentation manufacturer outlined in Table 3. Standardization of specific models and brands of test equipment is unnecessary as long as the test equipment used has performance specifications comparable to those listed in Table 1.

B. Test Plan for Breathing Work/Inhaled CO_2 Studies

(1) Measured Parameters:

(a) Oronasal or mouthpiece ΔP

(b) Breath-by-breath oronasal or mouthpiece CO_2 levels

(c) ΔP across other breathing loop components as required

(2) Controlled Parameters:

(a) Water temp: ambient

(b) Depth: 1 ATA increments to max test depth

(c) Breathing machine setup: see Table 1

(d) Relative humidity: ambient

(e) UBA orientation: diver in vertical position (Note: For certain closed-circuit UBA's measurement of static load should also be made in the prone position.)

TABLE 1

BREATHING RESISTANCE TEST CONDITIONS

VO2 AND VCO2 LPM STPD	RMV LPM	TV ℓ	FREQ	DIVER WORK RATE
0.90	22.5	1.50	15	Light
1.60	40.0	2.00	20	Moderate
2.50	62.5	2.50	25	Moderately Heavy
3.00	75.0	2.50	30	Heavy
3.60	90.0	3.00	30	Extreme *

* Ninety RMV represents an extreme work rate which can be sustained only for short durations. It has been achieved on manned wet dives at depths up to 1800 FSW and is included as a test parameter to determine the upper limits of a UBA's life support characteristics.

TABLE 2

CANISTER DURATION STUDY TEST CONDITIONS

DURATION (MIN)	VO2 AND VCO2 LPM STPD	RMV LPM	TV ℓ	FREQ	DIVER WORK RATE
4	0.90	23.0	2.00	11.5	Light
6	2.00	50.0	2.00	25.0	Moderate

TABLE 3

TEST EQUIPMENT

1. Breathing simulator with piston position transducer, CO_2 add system and exhaled gas temperature/humidity controller.

2. VALIDYNE Model DP-15 pressure transducer (oral pressure, canister pressure drop and inhalation/exhalation hose pressure drops).

3. Wet test box.

4. The heating and cooling systems will be used to control water temperature during the canister duration tests.

5. MFE Model 715M X-Y plotter for generating pressure-volume loops.

6. VALIDYNE Model CD-19 transducer readout.

7. BECKMAN 865 Infrared Analyzer for analysing CO_2 out of CO_2 absorbent canister.

8. Hyperbaric chamber complex.

9. ROYLYN gas supply pressure gauge (0.25% accuracy).

10. ROYLYN depth gauge (0.25% accuracy).

11. Test UBA: MK-16 Closed-Circuit Mixed-Gas UBA.

12. HYGRODYNAMICS Model 15-3050 Relative Humidity Sensor.

13. GOULD Brush Model 2600 Strip Chart Recorder.

14. YSI Model 700A Series Thermisters for monitoring CO_2 absorbent canister bed temperature.

15. DIGITEC Model 5820 Thermister Readouts.

16. APPLIED ELECTROCHEMISTRY Model S3-A oxygen analyser for measuring metabolic oxygen consumption.

17. PERKIN ELMER Model MGA 1100 Mass Spectrometer for breath-by-breath analysis of CO_2 washout in UBA oral cavity dead space.

TABLE 4

MANUFACTURER ADDRESSES

1. Validyne Engineering Corporation
18819 Napa Street
Northridge, CA 91324
Model DP15 Pressure Transducer
Model CD19 Carrier Demodulator

2. MFE Corporation
Keewaydin Drive
Salem, NH 03079
Model 715 Plotamatic X-Y Recorder

3. Beckman Instruments, Inc.
2500 Harbor Boulevard
Fullerton, CA 92634
Model 865 CO_2 Analyzer

4. 3D Instruments, Inc.
15542 Chemical Lane
Huntington Beach, CA 92649
Roylyn Precision Pressure Gauges (0.25% accuracy)

5. American Instrument Company
8030 Georgia Avenue
Silver Springs, MD 20910
Hygrodynamics Hygrometer Indicator (Model 15-3050)

6. Gould Inc.
Instrument Systems Division
3631 Perkins Avenue
Cleveland, OH 44114
2600 Series Recorder

7. United Systems Corp.
918 Woodley Road
Dayton, OH 45403
Digitec Model 5820 Digital Thermistor Thermometer with Series 700A Thermistor Probes

8. Applied Electrochemistry
735 N. Pastoria Avenue
Sunnyvale, CA 94086
Model S-3A Oxygen Analyzer

9. Perkin Elmer
2771 Garey Avenue
Pomona, CA 91766
Model MGA 1100

TABLE 4

MANUFACTURER ADDRESSES (continued)

10. Brooks Instrument Division
Emerson Electric Company
Hatfield, PA 19440
Model 5810 Thermal CO_2 Mass Flow Meter

11. Merriam Instruments
10920 Madison Avenue
Cleveland, OH 44101
Model LFE Laminar Flow Elements

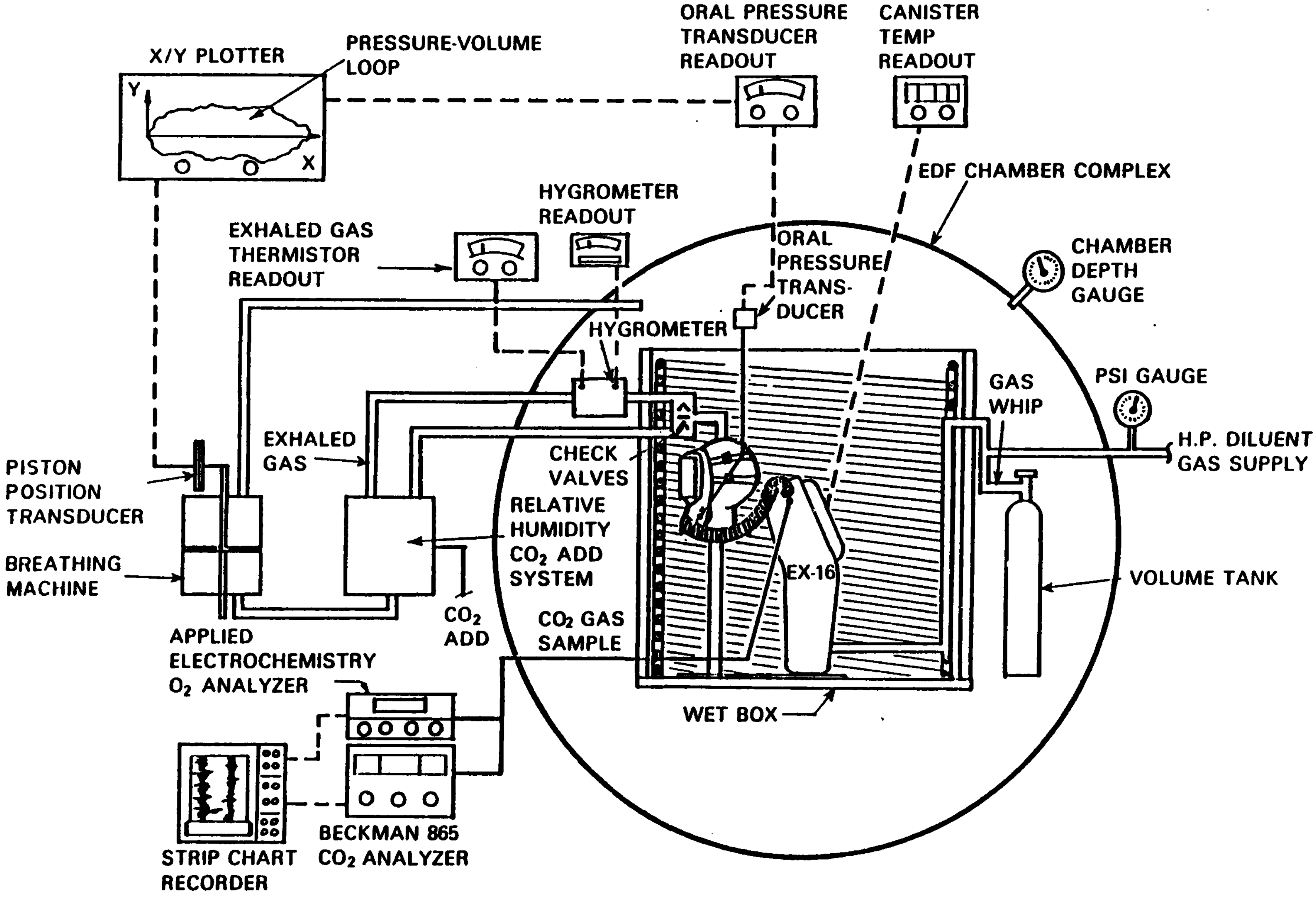


FIGURE 1 - TEST SETUP

(3) Procedure: At each depth of interest, testing under a given set of breathing simulator set points is done until stable readings are obtained.

(4) Data presentation:

(a) Typical ΔP waveforms

(b) Typical oronasal CO_2 waveform

(c) Typical pressure-volume loops

(d) Plots of peak inhalation/exhalation ΔP vs. depth at each RMV

(e) Work-of-breathing per liter (kg-m/ℓ) vs depth at each RMV

Note: Work-of-breathing is computed from the area inscribed by the pressure volume loops according to the formula:

$$\text{Work}/\ell \ (\text{kg-m}/\ell) = \frac{\text{Area}}{100\ (\text{TV})}$$

Area in units of $cmH_2O \times \ell$
TV in units of

(f) End expired and inspired oronasal CO_2 levels in % Surface Equivalent Value (SEV) (mean of 10 breaths) vs depth of each RMV

C. Test Plan for CO_2 Absorbent Canister Duration Studies:

(1) Measured Parameters:

(a) CO_2 (% SEV) levels at absorbent canister inlet and outlet

(b) Oronasal or mouthpiece CO_2 levels (% SEV) (breath by breath)

(c) Canister bed temperatures as required

(2) Test conditions:

(a) Water temp - within 2°F of desired temperature: Normal temperature test points are 30, 35, 40, 50, 60, and 70°F

(b) Depths - as required

(c) Breathing Machine setup: See Table 2

Note: Since tidal volume changes cannot be made rapidly on the Breathing Machine, this parameter is kept at 2ℓ for both test conditions.

(d) Relative humidity: 90 ± 2%

(e) UBA orientation: diver vertical

(f) Exhaled gas temperature: control maintained using the formula (expired gas temperature equals 24 + 0.32 times inspired gas temperature where inspired gas temperature is at ambient water temperature in umbilical-supplied UBA and assumed to be 10°C above ambient water temperature in self-contained apparatus): Texp = 24 + 0.32 Tin (degrees centigrade)

NOTE: If the inspired breathing gas is heated by external means, thermistors must be used to determine Tin, and this value used in the equation.

(3) Procedure: At each depth and temperature of interest, 4 minutes with the Breathing Machine setup in light work condition are followed by 6 minutes with Breathing Machine setup of moderate work (0.9 and 2.0 $\dot{V}CO2$, respectively) until a CO2 level of at least 1% SEV is observed in the canister outlet. CO_2 is added continuously through the Breathing Machine exhalation hose at the add rates shown in Table 2.

(4) Data presentation:

(a) Typical oronasal CO_2 waveforms

(b) Canister outlet CO_2 levels (% SEV) vs time

(c) Canister inlet CO_2 (% SEV) levels vs time

(d) Canister bed temperature vs time

(e) Times at which CO_2 level (% SEV) reaches 0.5 and 1.0% under each test condition

III. UNMANNED PERFORMANCE GOALS

A. UBA Categories. The various types of UBA are categorized into 5 groups according to their operational characteristics. Performance goals for each group are defined in Section B. Goals vary with each group depending upon maximum operating depth, breathing gas mixture and/or inherent state-of-the-art design limits.

Category 1: Open-circuit demand SCUBA regulators

Category 2: Open-circuit umbilical-supplied demand UBA (*i.e. full-face masks and dry helmets)

Category 3: Open-circuit umbilical-supplied free-flow UBA (i.e. full-face masks and dry helmets)

Category 4: Closed and semi-closed circuit diver breath driven UBA, *i.e. MK-15 and MK-11 type rigs with full face masks, mouthpiece or dry helmets

Category 5: Closed- and semi-closed circuit ejector or pump-driven UBA (push-pull) (i.e. MK-12 mixed-gas or MK-14 type rigs with dry helmets)

*Note: Full-face masks and dry helmets in categories 2 and 4 are assumed to have built-in oral-nasal masks or mouthpieces.

Performance goals in either work-of-breathing per liter and/or maximum ΔP are given in Table 4. Because of the nature of the pressure waveform for demand type UBA's, maximum ΔP is not considered appropriate for setting goals in category 1 and 2. In categories 3-5, the UBA will usually obey Bernoulli's law:

$$\Delta P_{max} \propto (\dot{V}\ max)^2\ P.\rho$$

$\dot{V}$ max = peak flow
P = ambient pressure (ATA)
ρ = gas density at 1 ATA
ΔP max = max Δp (from neutral to full inhalation or exhalation)

Also for a sine wave input
breathing work/L = $\frac{\pi\ \Delta P \text{ max}}{200}$

Thus once a ΔP max is chosen under one condition, in categories 3-5, the ΔP maximum and work-of-breathing are defined under all other conditions.

B. UBA Performance Goals (Tolerance is ± 10% of stated values)

Category 1: Breathing gas: Air
Maximum work-of-breathing is not to exceed 0.14 kg-m/ℓ at all depths and RMV up to and including 132 FSW and 62.5 RMV with 1000 psig supply pressure to the regulator first stage (see Note 1).

Category 2: Breathing gas: Air
(a) Maximum work-of-breathing is not to exceed 0.18 kg-m/ℓ at all depths and RMV up to and including 132 FSW and 62.5 RMV with supply pressures as per manufacturers requirements.

Breathing gas: HeO_2
(b) Maximum work-of-breathing is not to exceed 0.18 kg-m/ℓ at all depths and RMV up to and including 1000 FSW and 62.5 RMV with supply pressures as per manufacturers requirements (see Note 2).

(c) End inspired CO_2 levels at the mouth should be no greater than 2 mmHg more than the supply gas CO_2 at work rates up to 62.5 RMV at depths to 132 FSW on air and at depths to 1000 FSW on HeO_2 breathing gas, respectively.

Category 3: Breathing gas: Air

(a) Work-of-breathing is not to exceed 0.22 kg-m/ℓ and peak inhalation and exhalation presures are not to exceed 14 cmH_2O in either direction at depths to 200 FSW and 75 RMV (see Note 3).

(b) At the lowest driving pressure and longest umbilical length, gas flow rate to the UBA must be sufficient to maintain inhaled CO_2 less than or equal to 2.0% surface equivalent value at work rates up to and including 3.0 LPM CO_2 injection at 75 RMV.

(c) Helmet sound level is to be less than 90 dBA.

Category 4: Breathing gas: Air

(a) Work-of-breathing is not to exceed 0.18 kg-m/ℓ with peak inhalation and exhalation pressures not to exceed 11 cmH_2O in either direction at 75 RMV and 150 FSW (see note 3).

Breathing gas: HeO_2

(b) Work-of-breathing is not to exceed 0.22 kg-m/ℓ with peak inhalation and exhalation pressures not to exceed 14 cmH_2O in either direction at 75 RMV and 1500 FSW (see note 3).

(c) Static lung loading with no gas flow in the breathing loop should be 0.0 cmH_2O relative to the suprasternal notch in the upright position and + 10.0 cmH_2O in the prone position (see Figure 2).

(d) End inspired CO_2 levels at the mouth should be no greater than 2 mmHg more than canister effluent at work rates up to and including 3.0 LPM CO_2 injection.

(e) Helmet sound level to be less than 90 dBA.

(f) Unmanned canister duration time is the mean of at least 4 individual duration times done under identical conditions. The individual duration times are the times required for the canister effluent to consistently exceed 0.5% SEV during the work period of a canister duration study.

Category 5: Breathing gas: Air

(a) Maximum work-of-breathing is not to exceed 0.22 kg-m/ℓ with peak inhalation and exhalation pressures not to exceed 14 cmH_2O in either direction at 75 RMV and 200 FSW (see Note 3).

Breathing gas: HeO_2
(b) Maximum work-of-breathing is not to exceed 0.22 kg-m/ℓ with peak inhalation and exhalation pressures not to exceed 14 cmH_2O in either direction at 75 RMV and 1500 FSW (see note 3).

(c) Maximum allowable CO_2 level in the mask or helmet is to be less than 2.0% surface equivalent at work rates up to and including 3.0 LPM CO_2 injection (see note 4).

(d) Unmanned canister duration time is the mean of at least 4 individual duration times done under identical conditions. The individual duration times are the times required for the canister effluent to consistently exceed 0.5% SEV during the exercise period of a canister duration study (see note 4).

(e) Helmet sound level is to be less than 90dBA.

A summary of all performance goals in each category of UBA is given in Table 5.

Note 1: This goal is based upon a recent NEDU Report 2-80, "Evaluation of Commercially Available SCUBA Regulators", March 1980, by James R. Middleton, which evaluated commercially available SCUBA regulators. Only seven regulators met the above goal with another 23 being close. The value of 0.14 kg-m/ℓ at 62.5 RMV and 132 FSW was determined by examining the data to find the point at which state-of-the-art equipment significantly outperformed the rest of the group. The 75 RMV goals of Categories 3-5 is not attainable in Category 1 and 2 UBA's; and, consequently, the categories have performance goals with shallower depths and lesser RMV's than do Categories 3-5.

Note 2: The value of 0.18 kg-m/ℓ at 62.5 RMV represents the maximum performance that can be expected from state-of-the-art equipment in Category 2. It is based upon unmanned tests performed at NEDU.

The performance goal differs from Category 1 because conventional SCUBA regulators receive gas at the second stage at 125 to 150 psig overbottom pressure. Most demand regulators in Category 2 have overbottom pressure set at approximately 135 to 180 psig O/B at the diving console. The UBA then receives gas to the second stage at only 75 to 115 psig overbottom due to pressure losses in the umbilical and mask side block. Consequently, it is reasonable to expect a slightly reduced level of performance in Category 2 compared to Category 1.

Note 3: 75 RMV has been proven in both manned and unmanned testing as a reasonable performance goal in Categories 3 through 5. It will insure that the UBA is not the limiting factor in diver performance.

Note 4: Item (c) in Category 5 refers to ventilation sufficiency of the UBA helmet while item (d) in Category 5 refers to scrubbing efficiency of the CO_2 absorbent canister and both must be met simultaneously in this type of UBA.

PERFORMANCE GOALS

TABLE 5

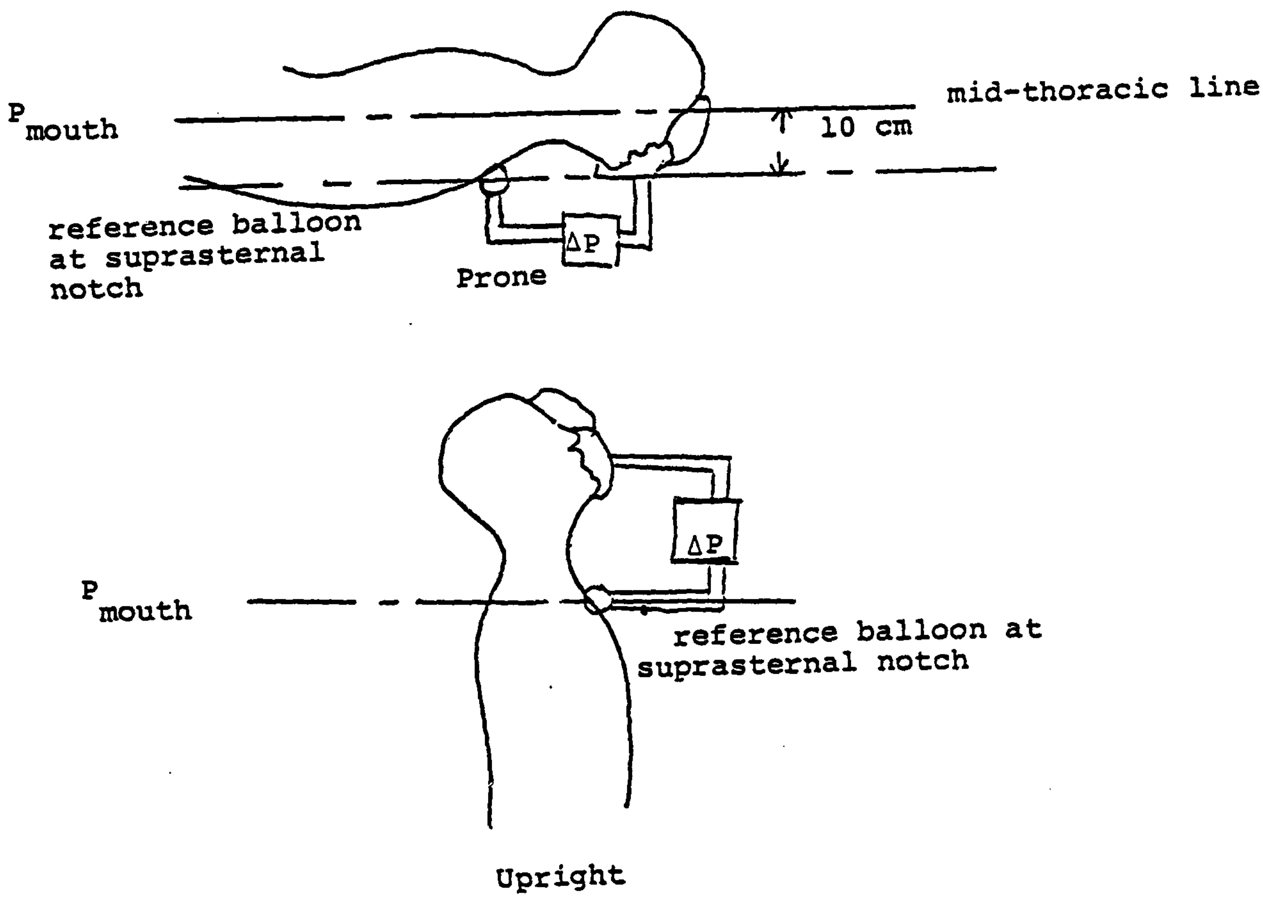
					CATEGORY 1 DEPTH 132 FSW AIR	CATEGORY 2 132 FSW AIR 1000 FSW HeO_2	CATEGORIES 3&5 200 FSW AIR 1500 FSW HeO_2		CATEGORY 4 150 FSW AIR		CATEGORY 4 1500 FSW HeO_2	
LPM	RMV LPM	TV ℓ	FREQ	PEAK FLOW RATE LPS	Work/ℓ kg-m/ℓ	Work/ℓ kg-m/ℓ	ΔP** CmH20	Work/ℓ kg-m/ℓ	ΔP** CmH20	Work/ℓ kg-m/ℓ	ΔP** CmH20	Work/ℓ kg-m/ℓ
0.90	22.5	1.5	15	1.18			1.5	0.02	1.1	0.02	1.5	0.02
1.60	40.0	2.0	20	2.09			4	0.06	3.3	0.05	4	0.06
2.50	62.5	2.5	25	3.27	0.14*	0.18*	10	0.15	7.6	0.12	10	0.15
3.00	75.0	2.5	30	3.93			14	0.22	11.0	0.18	14	0.22
3.60	90.0	3.0	30	4.71			20***	0.32	16.4***	0.25	20***	0.32

*Categories 1 and 2 are not capable of making the 75 RMV performance requirements at their maximum operating depths. State-of-the-art in open-circuit demand UBA is such that 62.5 RMV is the absolute limit for reasonable breathing work values at the present time.

**ΔP max is measured from neutral (no flow) to full inhalation or exhalation.

***3.60 V_{O_2} and 90 RMV is of data interest but 75 RMV is the actual performance goal.

FIG. 2



In the prone position, the no-flow mouth pressure (P_{mouth}) should be the same as the hydrostatic pressure at the mid-thoracic line. A differential pressure transducer (ΔP) connected between the oronasal mask and a pressure reference balloon at the suprasternal notch would read +10 cm H_2O since the suprasternal notch is usually 10 cm below the mid-thoracic line.

In the upright position, P_{mouth} should be at the same level as th suprasternal notch so that a differential pressure tranducer connecte between the oronasal mask and the reference balloon would read 0 cm H

References

1. NEDU Report 2-78, "Second Manned Evaluation of the Prototype Mark 12 SSDS Helium-Oxygen Mode," R.K. O'Bryan

2. NEDU Report 4-78, "Maximal Work Capacity of Man at 43.3 ATA," R.K. O'Bryan

3. NEDU Report 11-78, "Manned Evaluation of MK 1 SLSS," J.L. Zumrick

4. NEDU Report 13-78, "Manned Evaluation of the Mark 14 Closed-Circuit Saturation Diving System," J.L. Zumrick

5. NEDU Report 5-79, "Evaluation of Modified Draeger LAR V Closed-Circuit Oxygen Rebreather," James R. Middleton

6. NEDU Report 9-79, "Evaluation of the Diving Systems International Superlite 17B Helmet," James R. Middleton

7. NEDU Report 2-80, "Evaluation of Commercially Available Open-Circuit SCUBA Regulators," James R. Middleton

8. NEDU Report 3-80, "Unmanned Evaluation of U.S. Navy MK 11 Mod 0 Semi-Closed-Circuit Mixed-Gas UBA," James R. Middleton

9. NEDU Report 5-80, "Improved Life Support Capability of the MK 11 Semi-Closed-Circuit UBA by Modification of the Carbon Dioxide Absorbent Canister," C.A. Piantadosi, E.D. Thalmann, and W.H. Spaur

10. NEDU Report 9-80, "Unmanned Evaluation of U.S. Navy EX-16 UBA Pre-Production Model," James R. Middleton

11. NEDU Report 13-80, "Manned Evaluation of the Pre-Production MK-16 UBA," C.G. Gray and E.D. Thalmann

12. NCSC Hydrospace Lab Note #33-77 MK 12 SSDS Flow Test (Air Mode)

13. NCSC Hydrospace Lab Note #3-77 Recirculator System Flow Test (MK 12 SSDS Mixed Gas Mode)

14. NCSC Hydrospace Lab Note #9-77 MK 12 SSDS Total System Flow Test Series II

Appendix A

Reports Superceded by NEDU Report -81

1. NEDU Report 19-73, "Proposed Standards for Evaluation of Breathing Resistance of Underwater Breathing Apparatus," 1-30-74, S.D. Reimers

2. NEDU Report 23-73, "USN Procedures for Testing Breathing Characteristics of Open-Circuit SCUBA Regulators," 12-11-73, S.D. Reimers

3. NEDU Report 19-74, "Testing Procedures for Closed-Circuit and Semi-Closed-Circuit Underwater Breathing Apparatus," 1-29-74, S.D. Reimers

4. NEDU Report 20-74, "Testing Procedures for Open-Circuit Air Diver Helmets and Semi-Closed-Circuit Mixed-Gas Diving Helmets," 12-18-73, S.D. Reimers

APPENDIX C

NAVY EXPERIMENTAL DIVING UNIT

TEST PLAN 84-07

1. <u>Test Title</u>. Unmanned Evaluation of a Prototype Demand SCUBA Regulator (MILLER EX-1).

2. <u>Test Number</u>. 84-07.

3. <u>References</u>

(a) NEDU Report 9-79.

(b) NEDU Report 3-81.

(c) NEDU Report 2-80.

4. <u>Introduction</u>. The purpose of this test is to:

a. Evaluate the performance and test the design concept of a new high performance prototype demand breathing regulator, the MILLER EX-1, built by LT Ken Miller, USN as a part of a masters thesis topic at MIT, Cambridge, Massachusetts. This device, which is a totally new concept in demand valves, has potential application to the U.S. Navy saturation diving program for use with the current MK I MOD S mask.

b. Measure external respiratory work at various RMV rates as a supplementary guide for regulator evaluation.

c. This is an internal test. The results will be used to determine if the prototype meets current NEDU performance goals for Category II open circuit demand regulators as specified in NEDU Report 3-81.

5. <u>Program</u>

a. Duration of test: 3 days (including set up, calibration and post test procedures).

b. Number of hours to be worked each test day: approximately 8.

c. Dates of test: 30, 31 January and 1 February 1984.

6. <u>Preliminary Arrangements</u>

a. The prototype demand SCUBA regulator will be supplied for the test by the designer, LT Miller, USN. LT Miller will be present during all phases of the evaluation to both observe and advise T&E personnel.

b. The Test & Evaluation Division will supply all other necessary equipment required to complete the evaluation.

c. A simulated umbilical supplied diving system will be fabricated to support the evaluation. The system will consist of a five foot length of 0.5 inch inside diameter "SWAN" hose being connected to C Chamber air supply penetrator. The SWAN hose will connect into a 3/8 inch ID U.S. Divers, Corp. Royal Aqualung intermediate pressure hose, which in turn,

will supply the prototype regulator. A first stage SCUBA regulator will not be used to supply the EX-1 in order to evaluate solely the performance of prototype demand valve.

d. The demand regulator cracking pressure will be pre-set to 0.50 inches of H_2O.

e. Chamber C in the EDF test complex will be used to conduct this test.

7. Test Procedure

a. Equipment used:

(1) C Chamber Breathing machine.

(2) Validyne pressure transducers w/1.00 psid diaphragm (oral pressure).

(3) Chamber "C" test arc.

(4) Validyne pressure transducer w/100 psid diaphragm (demand regulator supply pressure) (test #1 at 50 psig overbottom).

(5) Validyne pressure transducer w/200 psid diaphragm (demand regulator supply pressure) (test #2 at 165 psig overbottom).

(6) Validyne pressure transducer w/50 psid diaphragm (P drop in 3/8 inch ID Royal Aqualung intermediate pressure hose).

(7) One X-Y plotter.

(8) Validyne CD-19 transducer readouts (3 each).

(9) EDF Chamber "C".

(10) One 3/8 inch ID Royal Aqualung intermediate pressure hose.

(11) One five foot length 1/2 inch ID SWAN hose with 3/8 inch ID block connector.

(12) One MILLER EX-1 prototype SCUBA regulator set at 0.50 in H_2O cracking pressure.

(13) External air supply pressure gauge.

(14) Gas supply regulator.

(15) Chamber depth gauge.

(16) Gould strip chart recorder.

(17) Breathing machine piston transducer.

(18) Bubble dampening mat.

b. Parameters to be controlled:

(1) Breathing rate / Tidal Volume / Respiratory Minute Volume

a. 15 BPM / 1.5 Liters / 22.5 RMV

b. 20 BPM / 2.0 Liters / 40.0 RMV

c. 25 BPM / 2.5 Liters / 62.5 RMV

d. 30 BPM / 2.5 Liters / 75.0 RMV

e. 30 BPM / 3.0 Liters / 90.0 RMV

(2) Exhalation/inhalation time ratio: 1.00/1.00.

(3) Breathing waveform: sinusoid.

(4) Air supply pressure: 50 and 165 psig overbottom at all depths.

(5) Incremental stops 0 to 198 FSW at 33 FSW increments and 300 FSW.

c. Parameters to be measured:

(1) Inhalation peak pressure (cmH_2O).

(2) Exhalation peak pressure (cmH_2O).

(3) Pressure vs volume plots.

(4) O/B pressure supplied to the 3/8 inch ID Royal Aqualung intermediate pressure hose (psig).

(4) Change in dynamic O/B pressure across the Royal Aqualung intermediate pressure hose (psig).

d. Parameters to be computed: respiratory work from pressure vs volume plots (kg•m/l).

e. Data to be plotted:

(1) Inhalation max pressure at each depth and RMV.

(2) Exhalation max pressure at each depth and RMV.

(3) Respiratory work at each depth and RMV.

(4) Overbottom supply pressure at each depth and RMV.

(5) Change in dynamics O/B pressure across the 3/8 inch ID Royal Aqualung intermediate pressure hose at each depth and RMV.

f. Test plan:

(1) (a) Ensure that the prototype demand regulator is set to the designer's specification, a cracking pressure of 0.50 inches H_2O is set and that the regulator is working properly.

(b) Chamber on surface.

(c) Calibrate transducers.

(d) Open air supply valve to test regulator and set supply pressure at 50 psig overbottom pressure.

(e) Adjust breathing machine to 1.5 liters tidal volume and 15 BPM and take data.

(f) Adjust breathing machine to 2.0 liters tidal volume and 20 BPM and take data.

(g) Adjust breathing machine to 2.5 liters tidal volume and 25 BPM and take data.

(h) Adjust breathing machine to 2.5 liters tidal volume and 30 BPM and take data.

(i) Adjust breathing machine to 3.0 liters tidal volume and 30 BPM and take data.

(2) (a) Pressurize chamber to 33 FSW and repeat steps (1)(d)-(1)(i).

(b) Pressurize chamber to 66 FSW and repeat steps (1)(d)-(1)(i).

(c) Pressurize chamber to 99 FSW and repeat steps (1)(d)-(1)(i).

(d) Pressurize chamber to 132 FSW and repeat steps (1)(d)-(1)(i).

(e) Pressurize chamber to 165 FSW and repeat steps (1)(d)-(1)(i).

(f) Pressurize chamber to 198 FSW and repeat steps (1)(d)-(1)(i).

(g) Pressurize chamber to 300 FSW and repeat steps (1)(d)-(1)(i).

(3) Set supply pressure at 165 psig overbottom pressure and repeat steps (1)(e) through (2)(g).

8. Post Test Arrangements. Remove T&E equipment from chamber complex, clean and store as necessary.

9. Personnel

a. Number required: four.

b. Duty: T&E Division personnel, test director, chamber operator and instrumentation technician; project officer and designer.

10. Safety Rules and Precautions. As specified in NEDU safety manual for chamber operators and in accordance with current EDF OP's and EP's.

11. Logistic Support Required. Air supply required:

a. Using the EDF Chamber "C" with floodable volume of 640 cubic feet, two compressions to 300 FSW will require 12,916.36 cubic feet of air.

b. Air supply to the prototype demand regulator based on average conditions of 40 LPM RMV, minutes of operation at 300 FSW; 1,816.36 cubic feet of air would be required.

Therefore total gas requirement is 14,732.72 cubic feet of air.

12. Communications. Communications between T&E console and inside of chamber during test set up.

13. Financial Aspects. Funding provided by SUPDIVE Tasking (Task # 82-18).

14. Security. Except for normal command structure, only personnel involved with testing will be allowed in the test complex.

15. Report Production. LT B.K. Miller, Jr. and T&E Division personnel will reduce all data. The Project Officer will draft a NEDU Technical Memorandum. No official NEDU report will be forthcoming due to the internal nature of this test.

APPENDIX D

TABLES/TEST DATA

TABLE D1 EX-1 MOD 0

WORK OF BREATHING (kg·m/l)
FOR 50 PSIG SUPPLY PRESSURE

Depth (FSW)	RMV (LPM)				
	22.5	40.0	62.5	75.0	90.0
0	.080	.093	.065	.064	.075
33	.124	.119	.106	.112	.130
66	.153	.123	.130	.151	.183
99	.183	.145	.171	.176	.270
132	.209	.163	.145	.180	*
165	.230	.172	.170	.338	*
198	.206	.167	*	*	*
300	.218	.229	*	*	*

* UNABLE TO TEST AT THESE RMV VALUES; SUPPLY PRESSURE DROP IS TOO LARGE.

TABLE D2 EX-1 MOD 0

WORK OF BREATHING (kg·m/l)
FOR 100 PSIG SUPPLY PRESSURE

Depth (FSW)	RMV (LPM)				
	22.5	40.0	62.5	75.0	90.0
0	.043	.066	.118	.149	NOTE 1
33	.044	.061	.066	.042	.067
66	.088	.074	.090	.108	.138
99	.111	.115	.123	.143	.150
132	.097	.139	.151	.192	.216
165	.182	.145	.198	.393	*
198	.184	.162	.226	.206	*
300	.265	.203	.260	*	*

NOTE 1: UNIT FREE FLOWED AT THIS TEST POINT.

* UNABLE TO TEST AT THESE RMV VALUES; SUPPLY PRESSURE DROP IS TOO LARGE.

TABLE D3 EX-1 MOD 0

PEAK EXHALATION/INHALATION PRESSURE (CmH_2O)
FOR 50 PSIG SUPPLY PRESSURE

E - EXHAUST
I - INHALE

Depth (FSW)	RMV (LPM)									
	22.5		40.0		62.5		75.0		90.0	
	E	I	E	I	E	I	E	I	E	I
0	4.0	7.0	7.0	7.5	7.0	7.5	6.0	7.0	8.5	6.0
33	10.0	10.5	7.0	12.0	7.5	10.5	9.0	10.0	10.0	9.0
66	5.0	14.0	7.0	15.0	8.5	13.5	12.0	13.0	16.5	11.5
99	6.0	16.5	8.0	18.0	11.5	17.0	15.0	18.0	14.5	34.0
132	5.5	19.0	7.5	22.5	10.0	19.0	13.0	18.5	**	
165	7.5	21.0	8.5	22.0	14.0	22.0	18.5	42.0	**	
198	6.5	22.0	8.0	24.0	**		**		**	
300	9.0	25.0	12.0	29.0	**		**		**	

** UNABLE TO TEST AT THIS RMV

TABLE D4 Ex-1 MOD 0

PEAK EXHALATION/INHALATION PRESSURE (CmH_2O)
FOR 100 PSIG SUPPLY PRESSURE

E - EXHAUST
I - INHALE

Depth (FSW)	RMV (LPM)									
	22.5		40.0		62.5		75.0		90.0	
	E	I	E	I	E	I	E	I	E	I
0	4.5	4.5	6.0	6.0	9.0	8.5	13.0	9.5	NOTE 1	
33	4.0	2.5	6.5	3.0	9.0	4.5	8.5	6.0	12.0	7.0
66	6.0	6.5	6.5	4.0	9.5	6.5	12.5	5.0	14.0	7.5
99	6.0	9.5	7.5	12.5	11.0	9.0	14.0	7.5	16.0	9.0
132	6.5	14.0	8.5	16.5	13.5	13.0	14.5	14.0	19.0	14.0
165	6.5	16.5	8.5	19.5	13.5	17.5	15.5	56.0	**	
198	6.0	20.5	11.0	20.5	16.0	20.5	18.5	17.5	**	
300	7.5	26.0	12.5	27.5	20.0	31.0	**		**	

** UNABLE TO TEST AT THIS RMV

AD-A144 809 DESIGN OF A SIMPLIFIED AIR REGULATOR FOR DIVERS(U) 2/2
MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF OCEAN
ENGINEERING B K MILLER JUN 84 N66314-70-A-0073

UNCLASSIFIED F/G 6/11 NL

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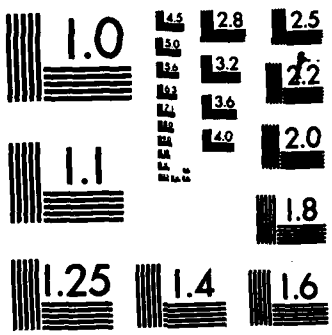

MICROCOPY RESOLUTION TEST CHART
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EX-1 MOD 0

TABLE D5

LINE PRESSURE LOSSES (PSIG)
FOR 50 PSIG SUPPLY PRESSURE

UMBILICAL / AIR SUPPLY AND TOTAL

RMV(LPM)	DEPTH IN FSW							
	0	33	66	99	132	165	198	300
22.5	0.0/4 (4.0)	0.4/10 (10.4)	0.8/12 (12.8)	0.8/12 (12.8)	0.8/12 (12.8)	1.0/14 (15.0)	2.0/16 (18.0)	2.4/18 (20.4)
40.0	0.8/5 (5.8)	2.0/10 (12.0)	2.8/14 (16.8)	3.2/15 (18.2)	4.0/16 (20.0)	4.0/20 (24.0)	4.8/20 (24.3)	6.4/26 (32.4)
62.5	1.8/8 (9.6)	2.8/11 (13.8)	4.0/15 (19.0)	4.8/16 (20.8)	7.2/20 (27.2)	9.6/24 (33.6)	---	---
75.0	2.0/8 (10.0)	3.6/12 (15.6)	4.8/15 (19.8)	7.2/18 (25.2)	9.2/24 (33.2)	9.6/24 (33.6)	---	---
90.0	2.2/9 (11.2)	4.0/13 (17.0)	6.4/18 (24.4)	8.4/21 (29.4)	9.2/24 (33.2)	---	---	---

IF NO VALUE IS SHOWN, NO DATA WAS RECORDED AT THAT POINT.

EX-1 MOD 0

TABLE D6

LINE PRESSURE LOSSES (PSIG)
FOR 100 PSIG SUPPLY PRESSURE

UMBILICAL / AIR SUPPLY AND TOTAL

RMV(LPM)	DEPTH IN FSW							
	0	33	66	99	132	165	198	300
22.5	---	0/0 (6.0)	.4/8.0 (8.4)	.8/12.0 (12.8)	.8/12.0 (12.8)	1.2/12.0 (13.2)	1.2/12.0 (13.2)	2.4/14.0 (16.4)
40.0	---	2.8/8.0 (10.8)	4.0/8.0 (12.0)	4.8/12.0 (16.8)	6.0/14.0 (20.0)	6.4/20.0 (26.4)	7.2/20.0 (27.2)	11.2/20.0 (31.2)
62.5	---	5.2/12.0 (17.2)	6.4/12.0 (18.4)	8.4/16.0 (24.4)	10.8/18.0 (28.8)	12.8/24.0 (36.8)	18.0/28.0 (46.0)	22.0/28.0 (50.0)
75.0	---	6.0/12.0 (18.0)	8.0/14.0 (22.0)	10.8/18.0 (28.8)	15.6/22.0 (37.6)	15.2/28.0 (43.2)	20.8/32.0 (52.8)	---
90.0	---	7.2/16.0 (23.2)	9.6/16.0 (25.6)	14.4/20.0 (34.4)	17.2/24.0 (41.2)	---	---	---

IF NO VALUE IS SHOWN, NO DATA WAS RECORDED AT THAT POINT.

TABLE D7 EX-1 MOD 1

WORK OF BREATHING (kg·m/ℓ)
FOR 50 PSIG SUPPLY PRESSURE

Depth (fsw)	RMV (LPM)				
	22.5	40.0	62.5	75.0	90.0
0	0.120	0.122	0.117	0.096	0.098
33	0.125	0.124	0.109	0.101	0.095
66	0.119	0.118	0.106	0.103	0.148
99	0.112	0.109	0.100	0.124	0.392
132	0.103	0.093	0.106	0.258	*
165	0.088	0.086	0,161	*	*
198	0.089	0.083	0.392	*	*
300	0.099	0.121	*	*	*

*Unable to test at these RMV values;
supply pressure drop is too large.

TABLE D8 EX-1 MOD 1

WORK OF BREATHING (kg·m/ℓ)
FOR 80 PSIG SUPPLY PRESSURE

Depth (fsw)	RMV (LPM)				
	22.5	40.0	62.5	75.0	90.0
0	.113	.115	*	*	*
33	.128	.134	.129	.127	.125
66	.148	.145	.139	.168	.163
99	.159	.155	.150	.170	.172
132	.162	.148	.173	.208	.241
165	.174	.172	.199	.232	**
198	.171	.165	.206	**	**
300	.174	.179	**	**	**

*Unable to test due to severe oscillations.

**Unable to test at these RMV values;
EX-1 peak inhalation pressure exceeds test recorder limits.

END

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